Effect of Pre- and Post-Coat Processing on the Fatigue Life of Coated Disk Alloys

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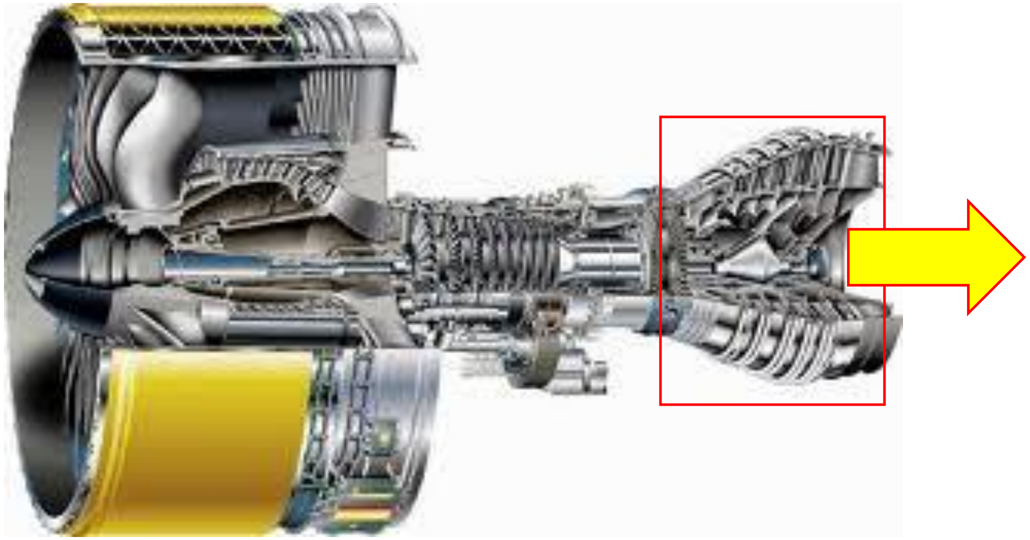
SOA turbine disks can operate up to ~704°C (1300°F) peak rim temperatures



One means of achieving future fuel burn and emission goals is to increase engine and disk temperatures.

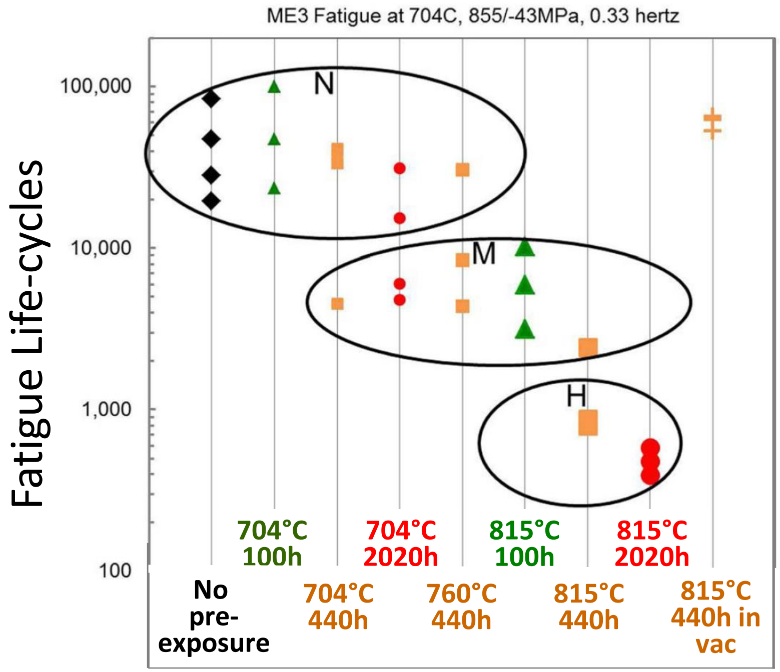
As a result, NASA has goals:

(1) to develop a hybrid polycrystal/single crystal turbine disk to operate at higher temperatures (up to 815°C) and,

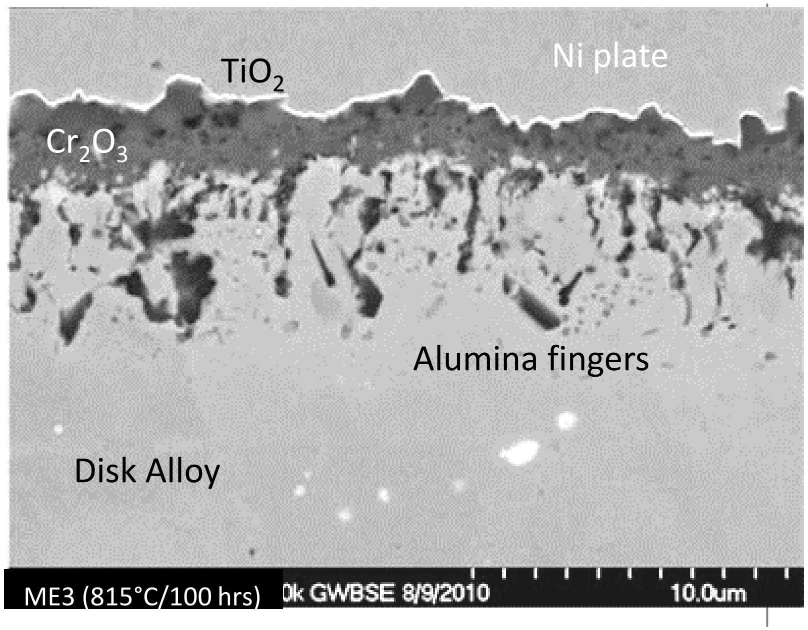
(2) protect those disks from oxidation and hot corrosion attack while maintaining low cycle fatigue (LCF) life.

Oxidation at disk temperatures of interest reduces the fatigue life of disk alloys

Notch fatigues lives of ME3 bars



Oxidized Surface of disk alloys (700-815°C)

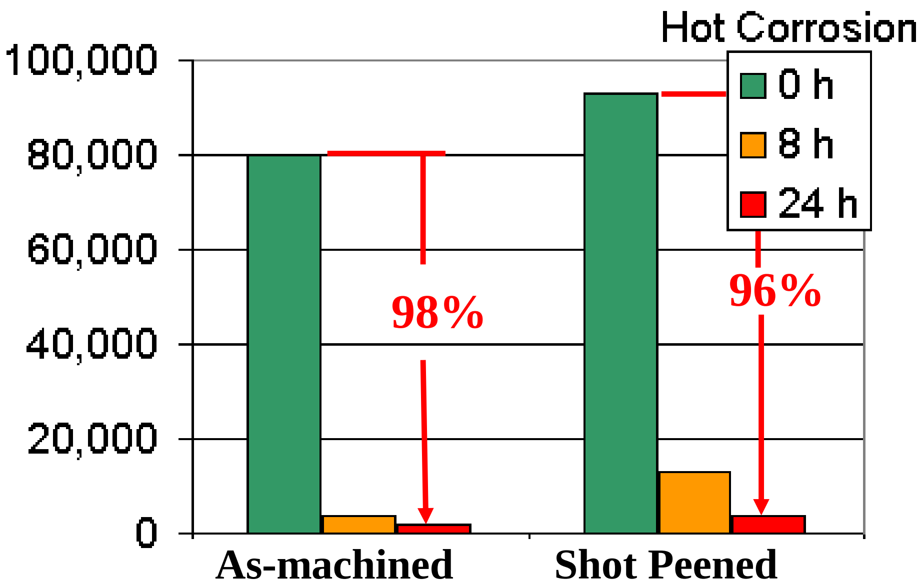


“…longer exposures near 704°C or higher temperature exposures can substantially degrade fatigue lives…”

Ref: Gabb, T. P., Sudbrack, C. K., Draper, S. L., MacKay, R. A., and Telesman, J., "Effects of Long Term Exposures on Fatigue of PM Disk Superalloys," *Materials Performance and Characterization*, Vol. 3, No. 2, 2014, pp. 44-67

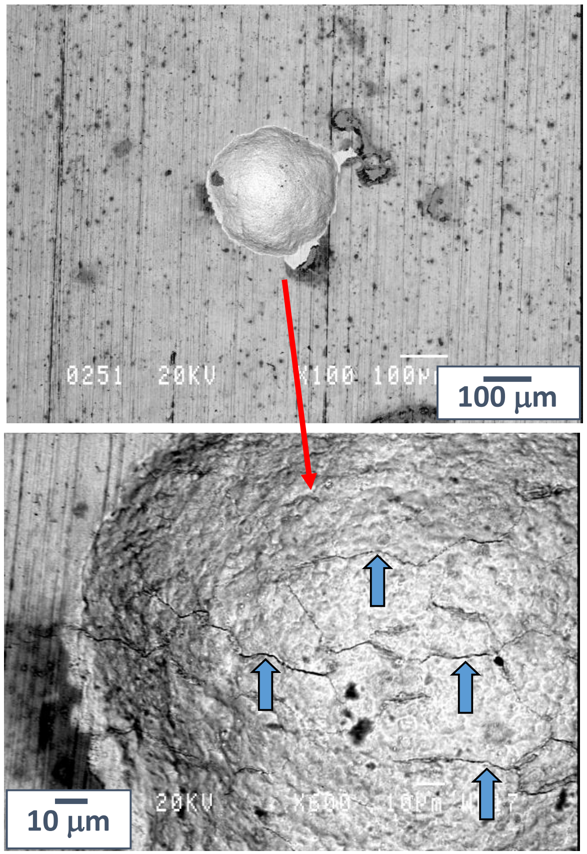
Hot corrosion at disk temperatures of interest reduces the fatigue life of disk alloys

Fatigue Life at 704°C (1300°F)



Ref: Gabb, et al., "The Effects of Hot Corrosion Pits on the Fatigue Resistance of a Disk Superalloy," Journal of Materials Engineering and Performance, Vol. 19, 77, 2010.

704°C



Corrosion pit in ME3

Hence, <u>conventional disks</u> operating at SOA temperatures and above (700-760°C), as well as future <u>hybrid disks</u> operating at higher temperatures, <u>will require protective coatings.</u>

Since disks are designed to resist low cycle fatigue cracking, which is dependent on crack initiation, the coating must not enhance crack initiation and degrade LCF life.

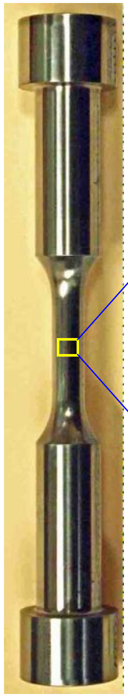
Last year, results on two similar advanced disk alloys were presented

- LSHR (Low Solvus, High Refractory)
- ME3

Weight Percent

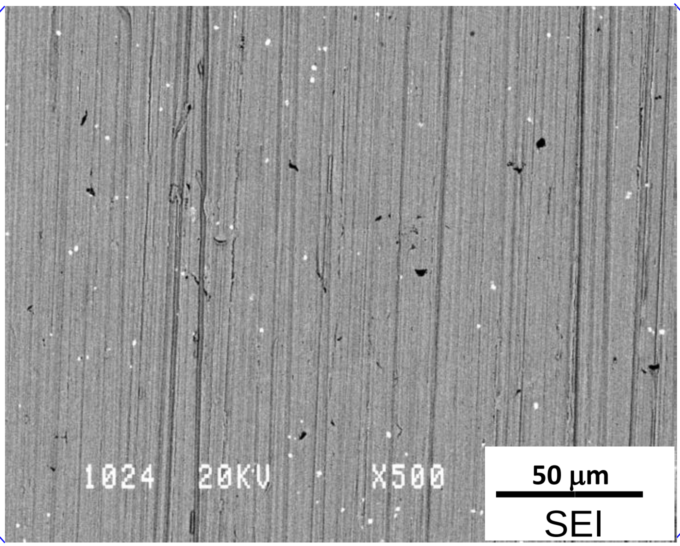
	Ni	Co	Cr	Al	Ti	W	Nb	Mo	Ta	Zr	B	C
LSHR	50.14	20.4	12.3	3.49	3.48	4.24	1.51	2.72	1.59	0.05	0.03	0.05
ME3	50.48	20.6	13.0	3.23	3.59	1.97	0.89	3.73	2.38	0.05	0.02	0.06

ME3

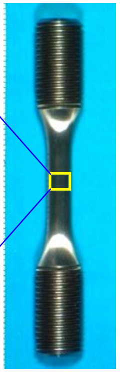


2 mm

Reduced gauge section is Low Stress Ground (LSG) + longitudinal polish (LP)



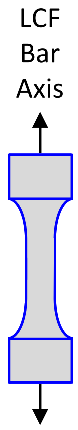
LSHR

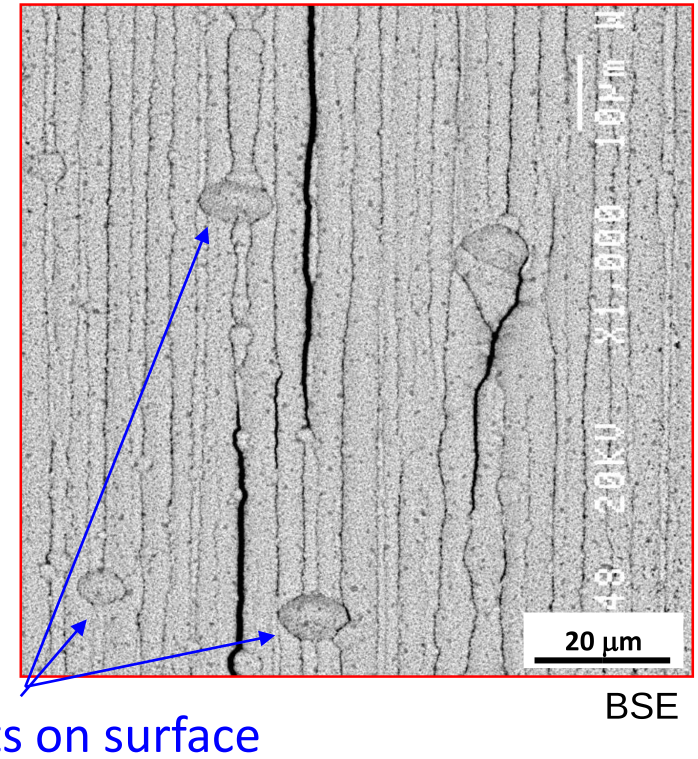


2 mm

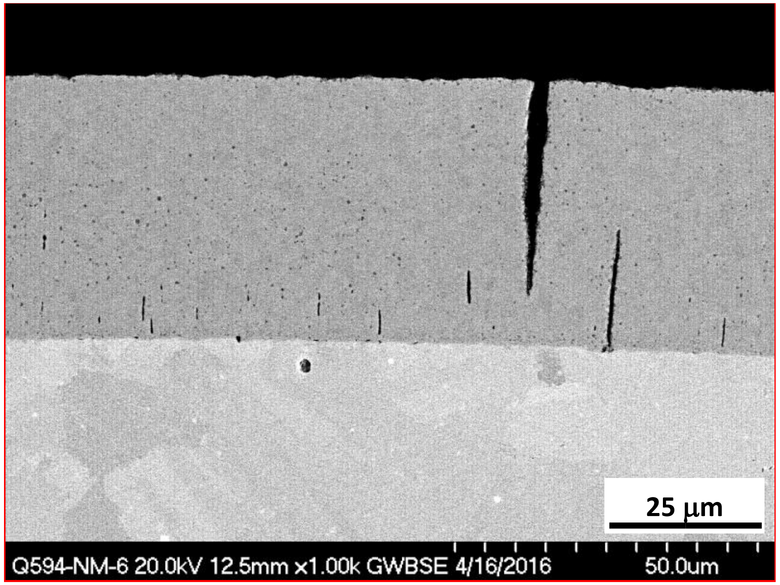
Both large ME3 bars and small threaded LSHR bars had the same polish in the reduced gauge section.

Coating texture follows longitudinal polishing marks on surface, creates longitudinal “cracks” or gaps.



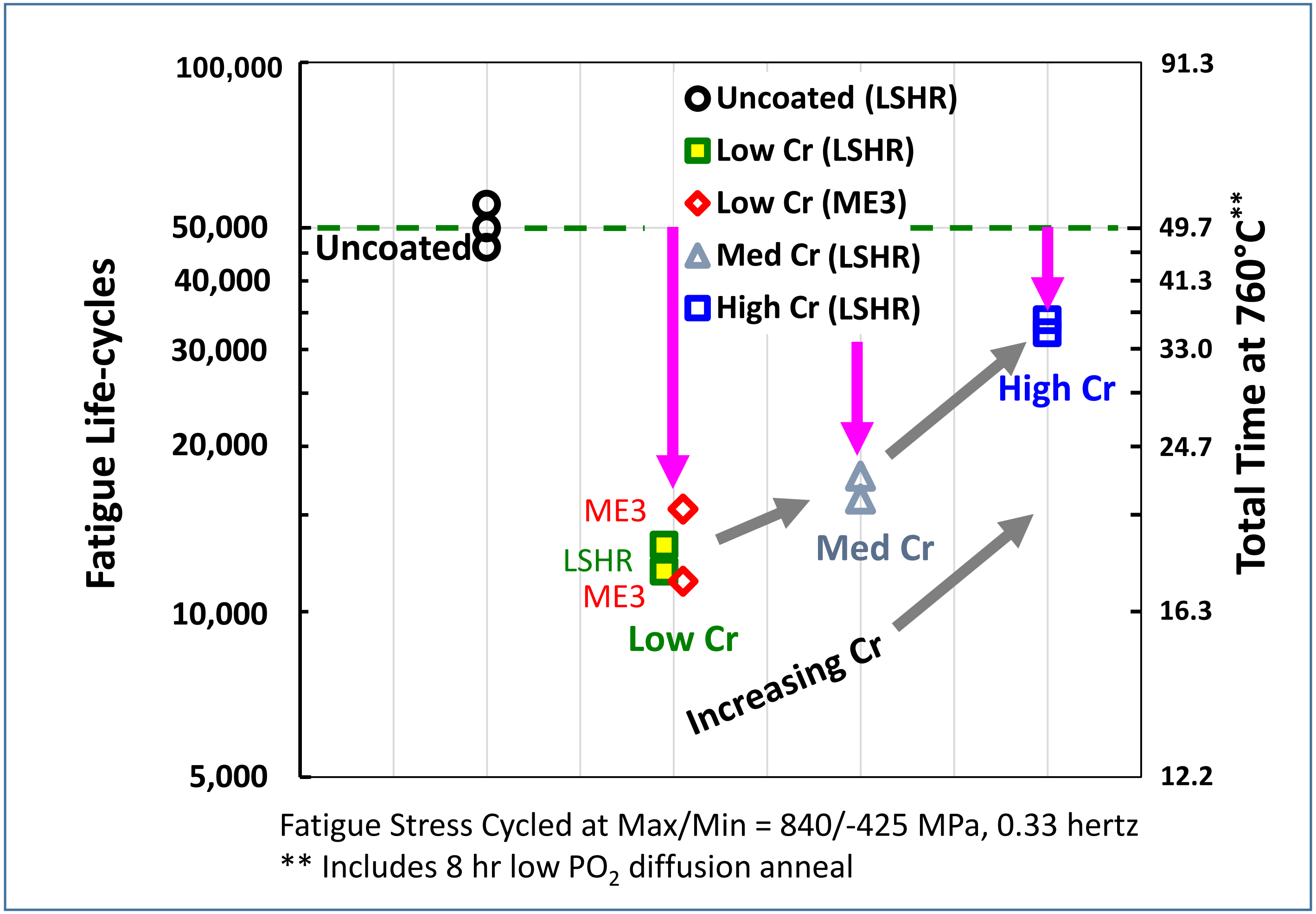


BSE



Coatings applied at SwRI, San Antonio, TX using plasma enhanced magnetron sputtering (PEMS)

Fatigue Life (No Shot Peening, No OX, No HC)



Fatigue life increases with Cr content of coating (Ni-45Cr best).

All coated bars have lower LCF life than uncoated bars.

Next follow-on study*

Grit blasting (alumina grit at 85 psi) of the LP surface to eliminate longitudinal polishing marks. Roughened surface was coated using High Power Impulse Magnetron Sputtering (HIPIMS) to deposit a Ni-45Cr-0.1Y coating

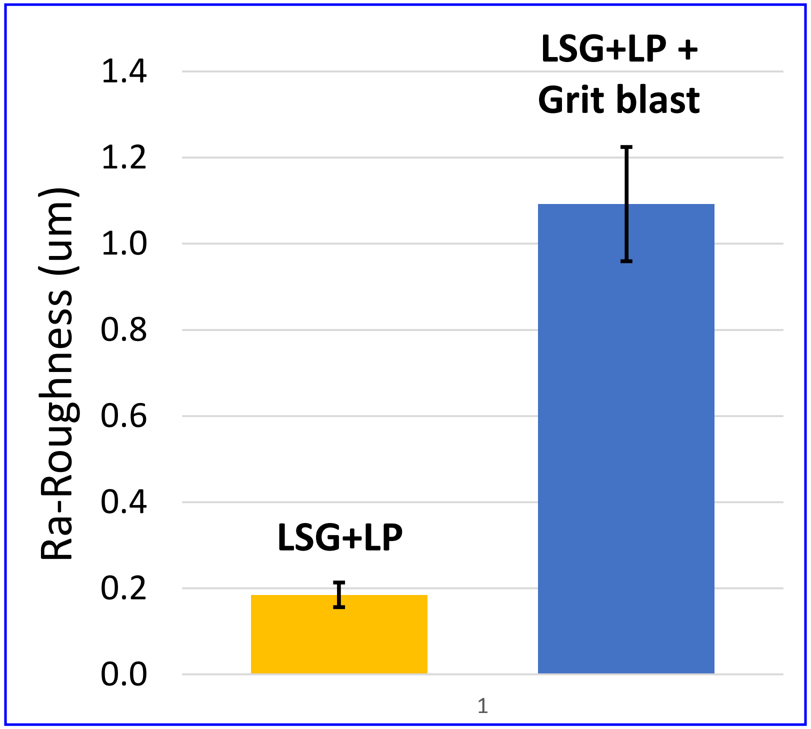
DOE Study involving 32 bars

Examine effect of:

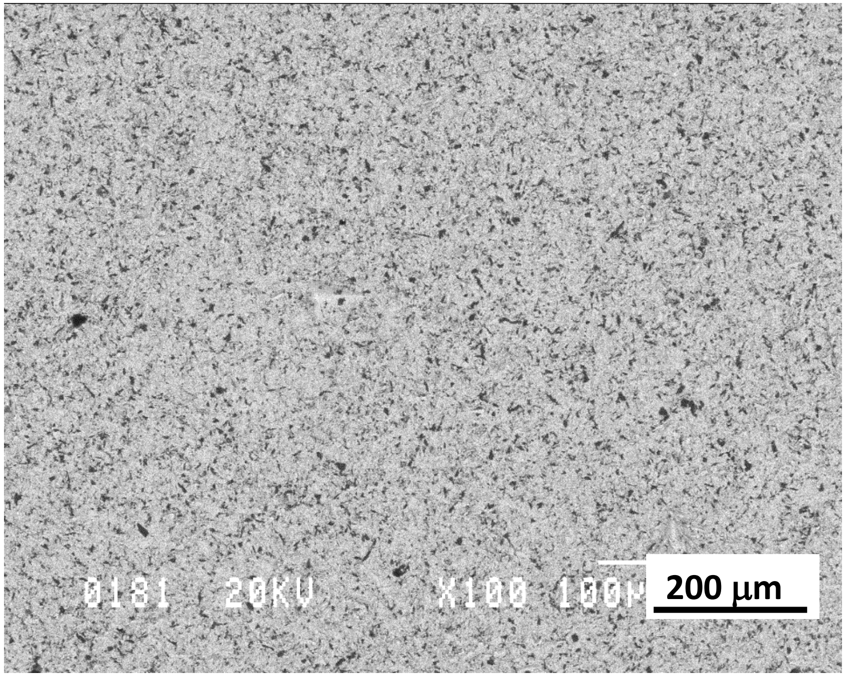
- Coated vs Uncoated
- Low and high shot peening (4N-100% vs 16N-200%)
- Diffusion anneal in air vs low PO_2 (10^{-17} atm O_2), 8h/760°C
- With and without oxidation exposure (500h/760°C)
- With and without hot corrosion exposure (50h/760°C with salt)

* Gabb, et al, The Effectiveness of a NiCrY-Coating on a Powder Metallurgy Disk Superalloy NASA/TM—2018-219885

Grit blasting of the LSG+LP surface (alumina grit at 85 psi) eliminated the longitudinal polishing marks and uniformly roughened the surface.



LSG + LP + Grit blast

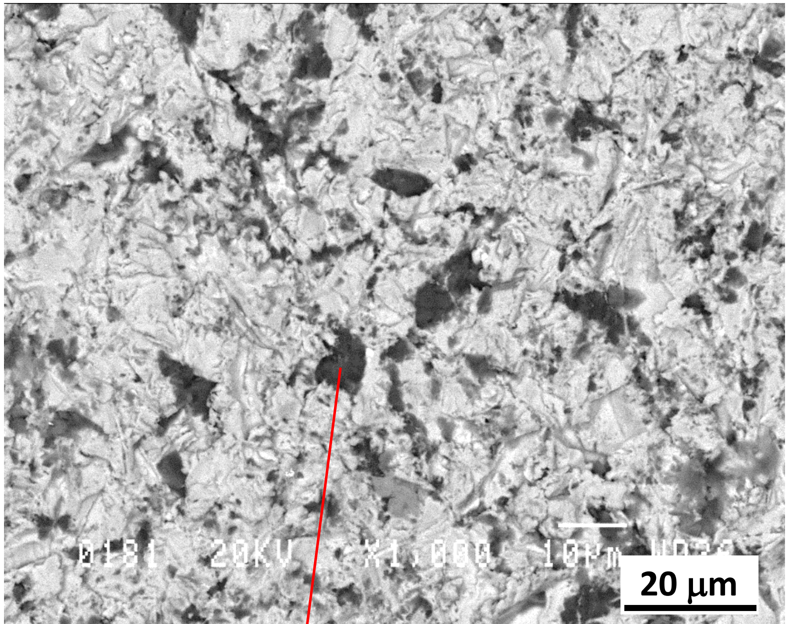


BSE

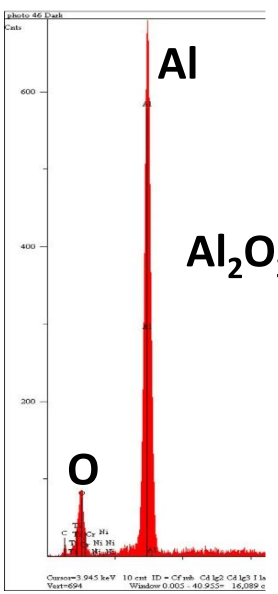
Longitudinal polishing lines eliminated.
Roughened surface was coated using HIPIMS with a Ni-45Cr-0.1Y coating.*

* Coatings applied at SwRI, San Antonio, TX.

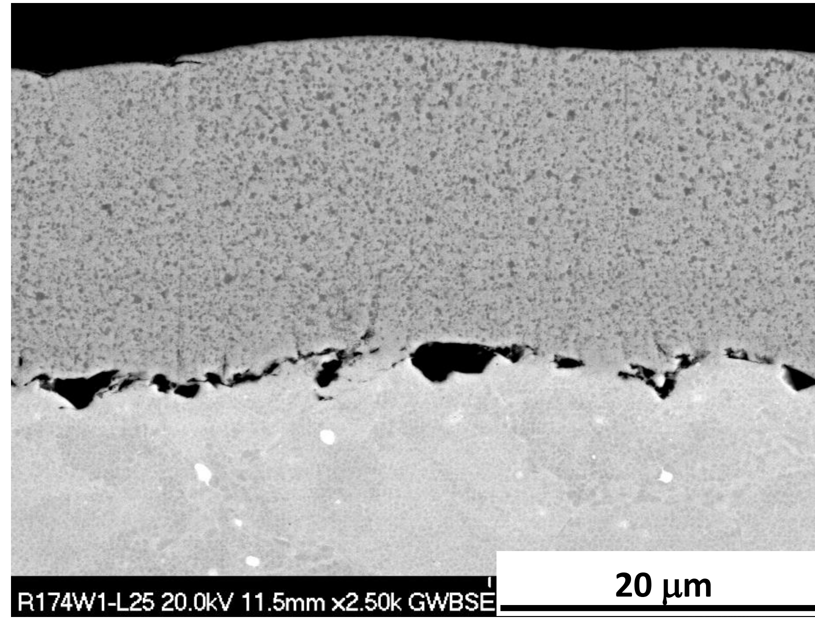
Alumina grit embedded in substrate



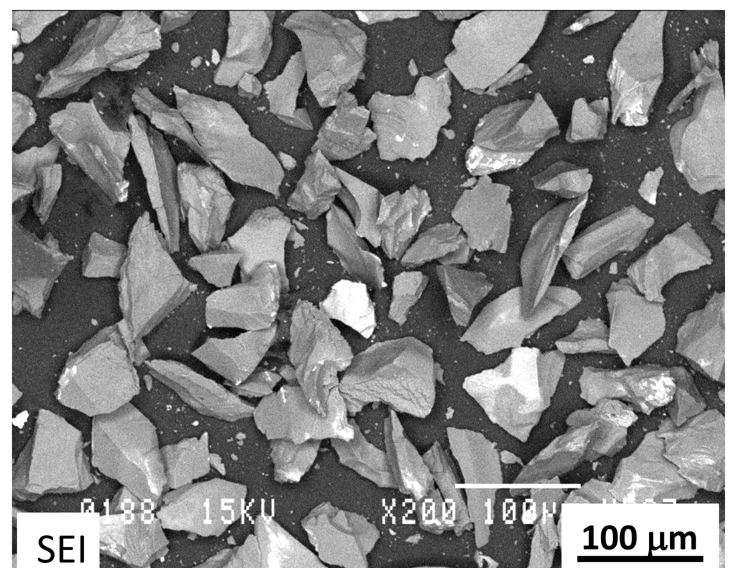
BSE



Al_2O_3 grit



BSE



Need to eliminate polishing marks but selected grit blast was too severe (grit embedded in surface)

What is the ideal pre-coat surface treatment for this application?

Purpose:

Examine pre-coat processing to maximize low cycle fatigue (LCF) life of coated disk alloys

Approach:

Examine four pre-coat processing treatments on the LCF life of a Ni-45Cr-0.1Y coated disk alloy

(1) Highly polished
(2) Wetblast
(3) Shot-peening at 8N-200%
(4) Shot-peening at 16N-200%

Standardized post-coat processing (identified in the previous study as beneficial: shot peening, diffusion anneal)

Standardized LCF Testing protocol:

- Coated versus uncoated (minimum of 2 bars)
- With and without environmental exposures
    - oxidation (OX)
    - hot corrosion (HC)

Experimental Procedures

1. Apply pre-coat treatments

   (Starting condition of all bars was LSG + LP (longitudinal polish)

   A. Highly polished at SWRI, San Antonio, TX

   B. Wetblast at Wetblast.com, Franklin, WI

      (80 psi, 4" from piece, 15% 300 glass bead)

   C. Shot peening at Metal Improvement Co., Cincinnati, OH

      1. 8N-200% (AMS 2432 using conditioned cut
      2. 16N-200% stainless steel wire (CCW14))

2. Characterize surfaces

   Surface roughness (Zygo 7200), SEM

3. Coating: Ni-45Cr-0.1Y applied at SWRI, San Antonio, TX (HIPIMS)

4. Post-coat shot peen the surface (16N-200%) (Metal Improvement)

5. Perform low PO_2 diffusion anneal (8 hrs, 760°C, PO_2 of 10^{-17} atm O_2)

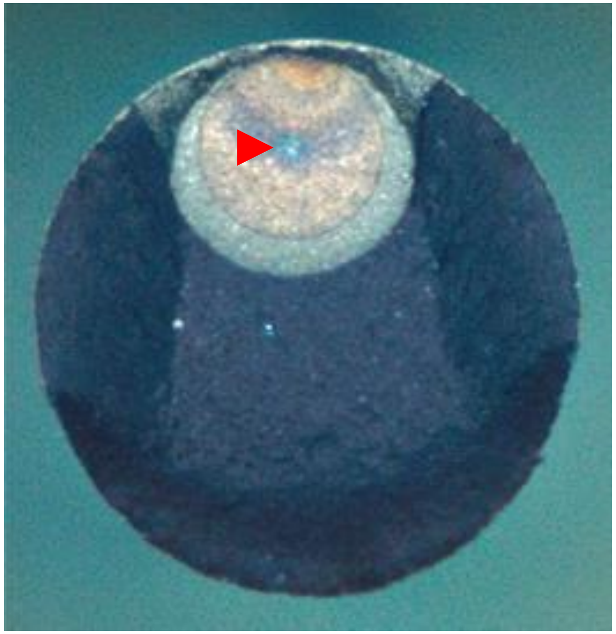
   - Flow UHP Ar over Ni foils to diffusion bond coating and substrate and promotes protective Cr_2O_3 formation

Experimental Procedures

1. Environmental exposures (half of coated bars)
    A. Oxidation exposure (500 hrs, 760°C (1400°F) in air)
    B. Hot corrosion exposure (2 mg/cm^2 eutectic 72% Na_2SO_4-28% $MgSO_4$ salt, 50 hrs, 760°C (1400°F) in static air), sonic water clean

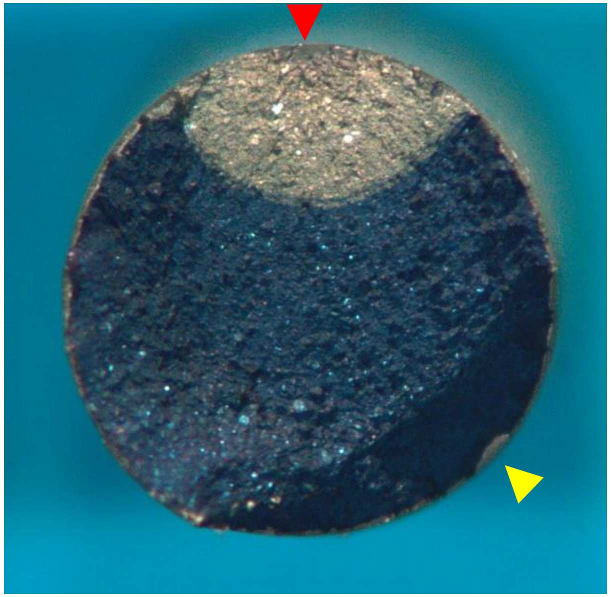
2. LCF Testing (760°C, 1400°F)
    A. 841/-427 Mpa, 0.33 hertz
    (Same LCF test parameters for previous tests)

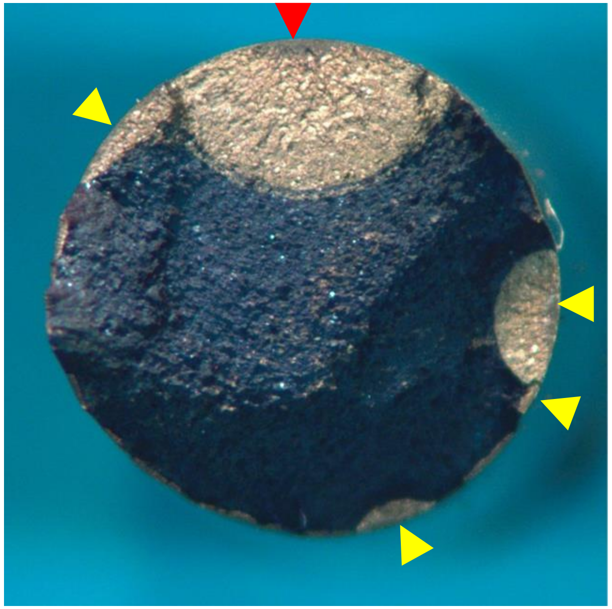
Internal initiated crack



Surface initiated crack

One or multiple crack initiation sites





Coated bars

(4 pre-coat surface conditions)

- Highly polished (4 bars)
- Wet-blast (4 bars)
- Shot peened at 8N-200% (4 bars)
- Shot peened at 16N-200% (4 bars)

Coated with Ni-45Cr-0.1Y

Uncoated bars

- LSG+LP (6 bars)

Shot peening 16N-200%

Diffusion anneal, 8h/760°C, Low PO_2 (10^{-17} atm O_2)

Oxidation exposure

(500h/760°C, air)

Hot corrosion exposure

(50h/760°C, Na-Mg sulfate salts, air)

LCF Testing (760°C)

841/-427 Mpa, 0.33 hertz

LCF Testing (760°C)

841/-427 Mpa, 0.33 hertz

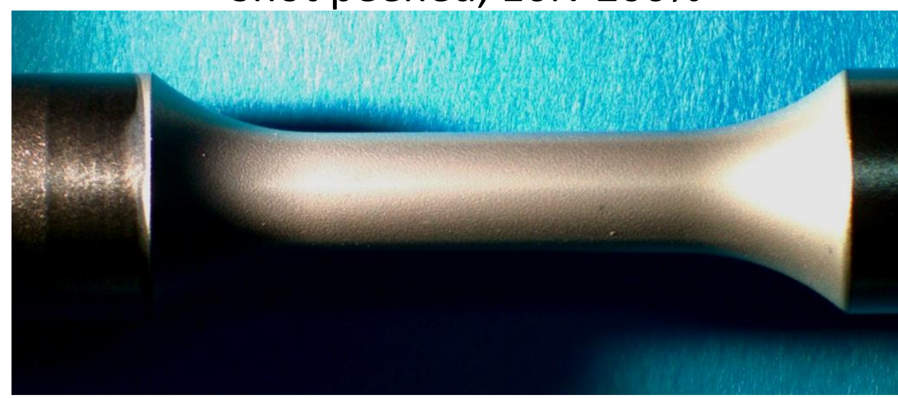
LCF bars after surface treatment

Highly polished

Wet-blast

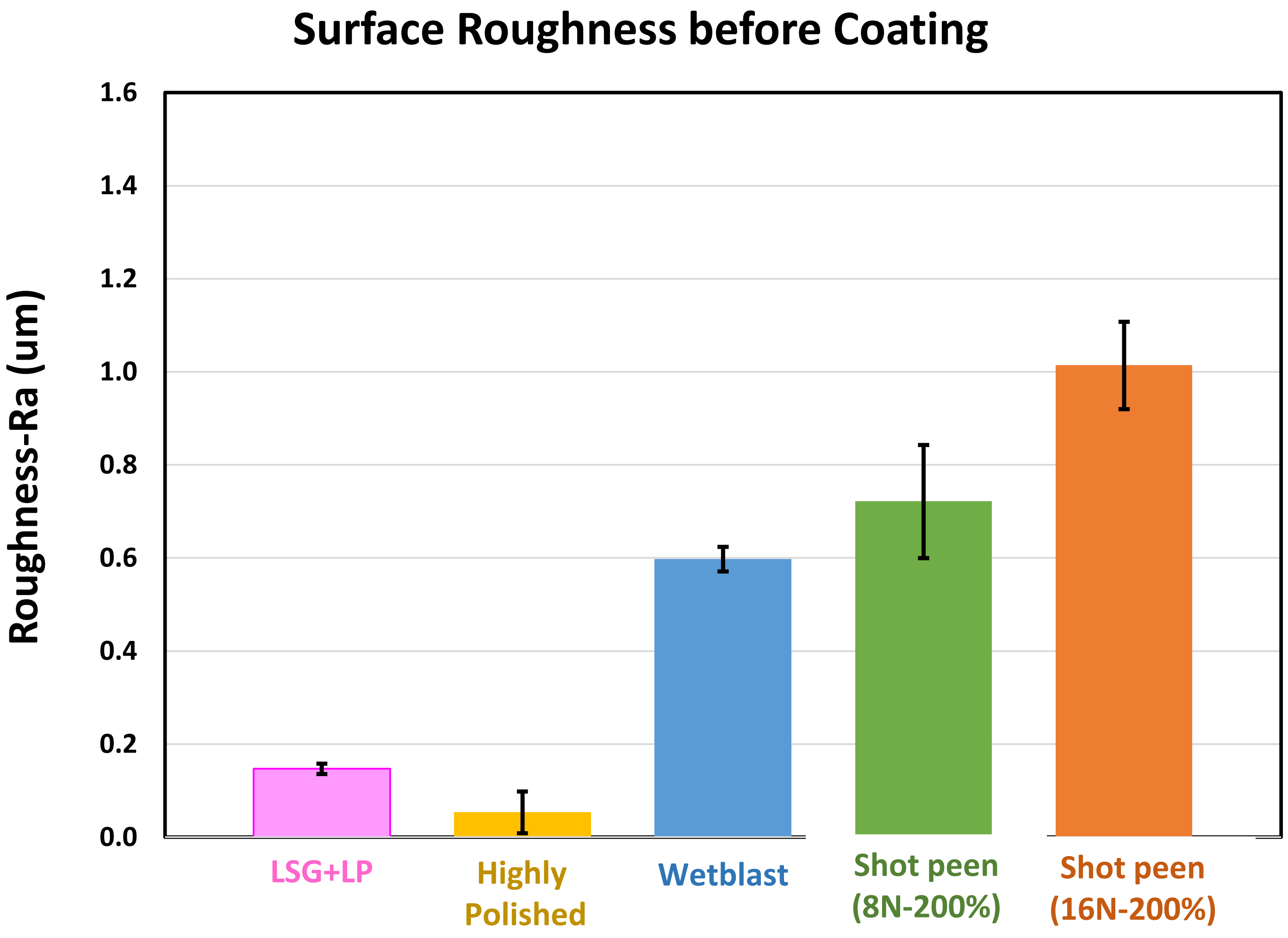
Shot peened, 8N-200%

Shot peened, 16N-200%

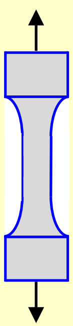


10 mm

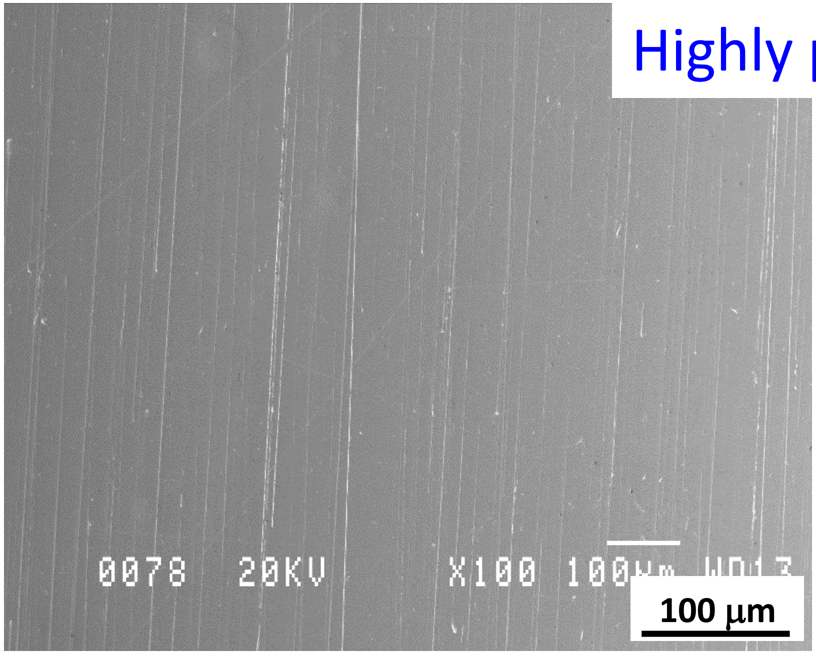
Surface Roughness after Surface Treatments

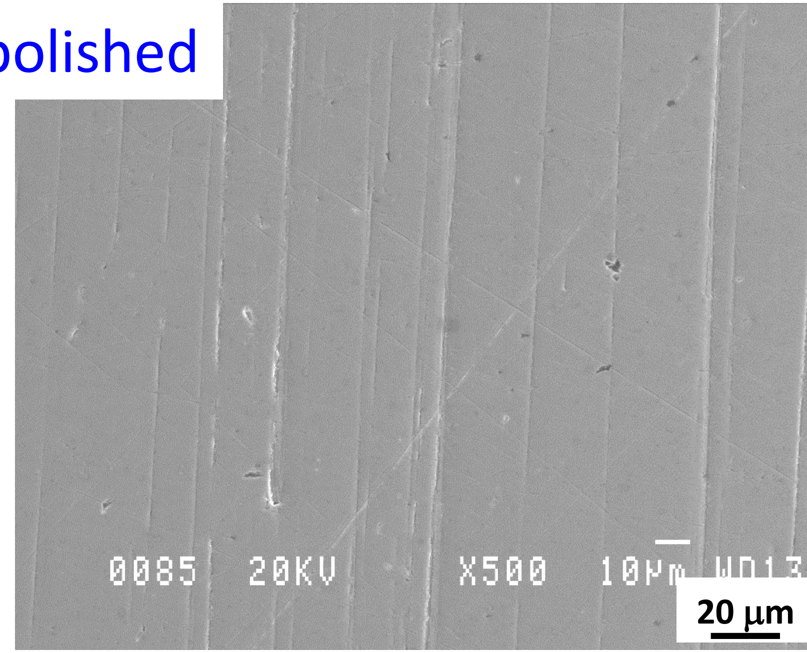


LCF
Bar
Axis

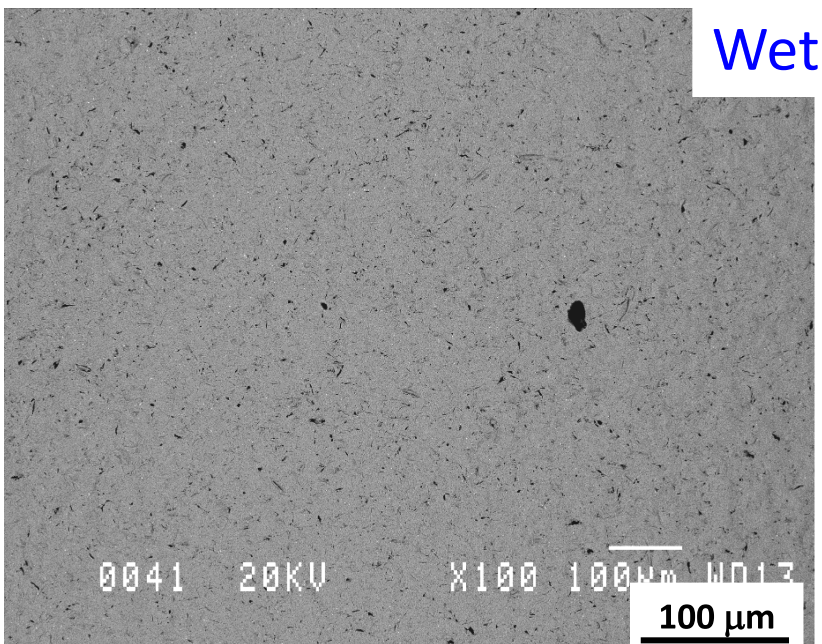


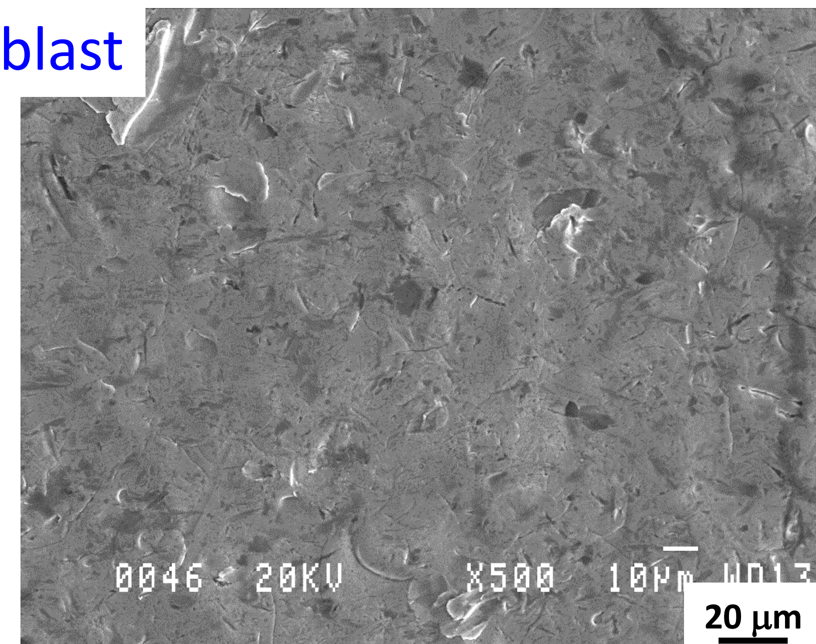
Highly polished



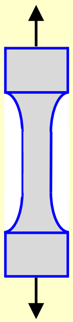


Wetblast

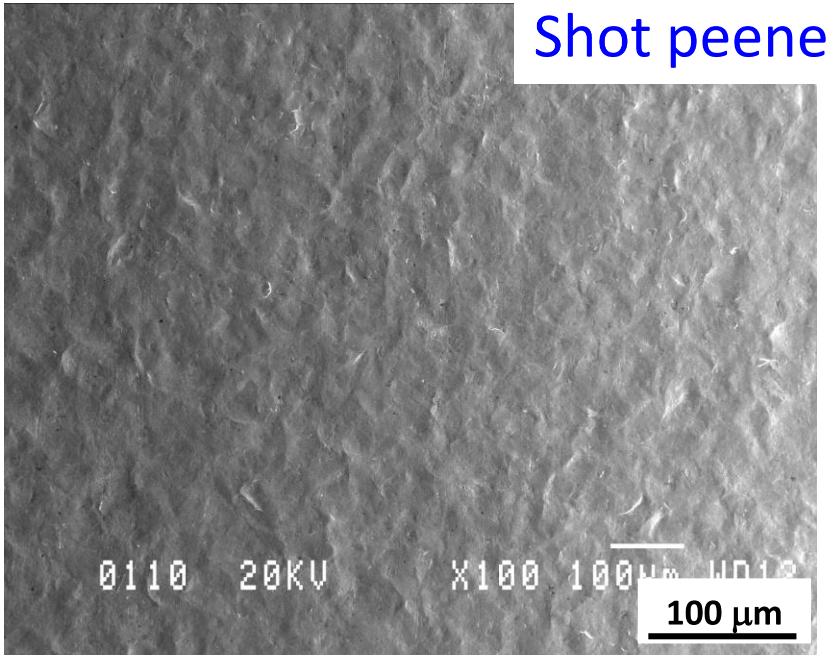


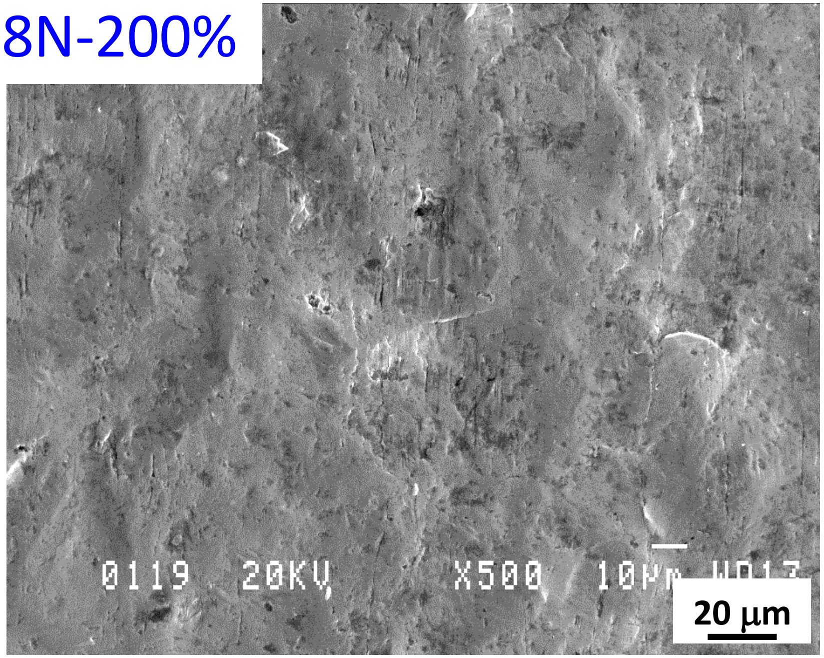


LCF
Bar
Axis

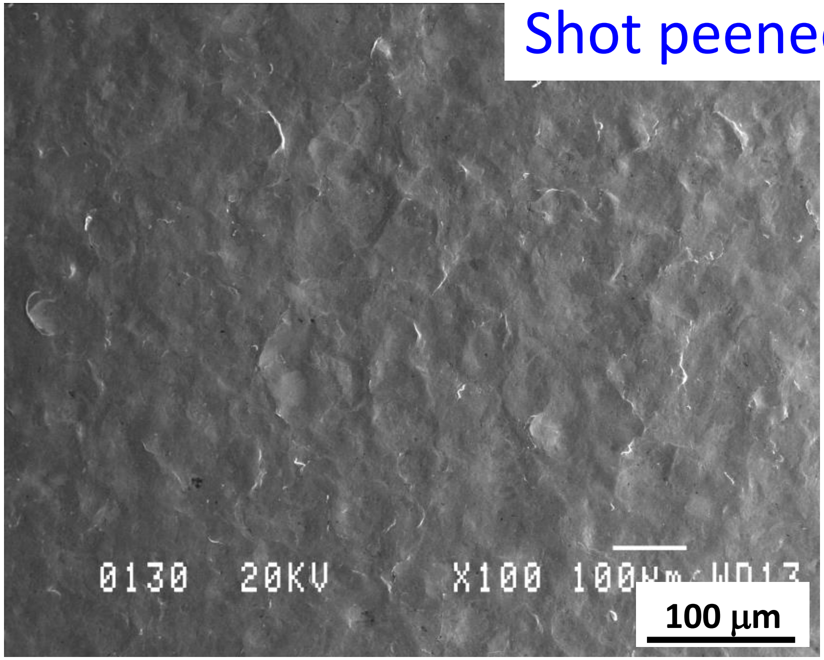


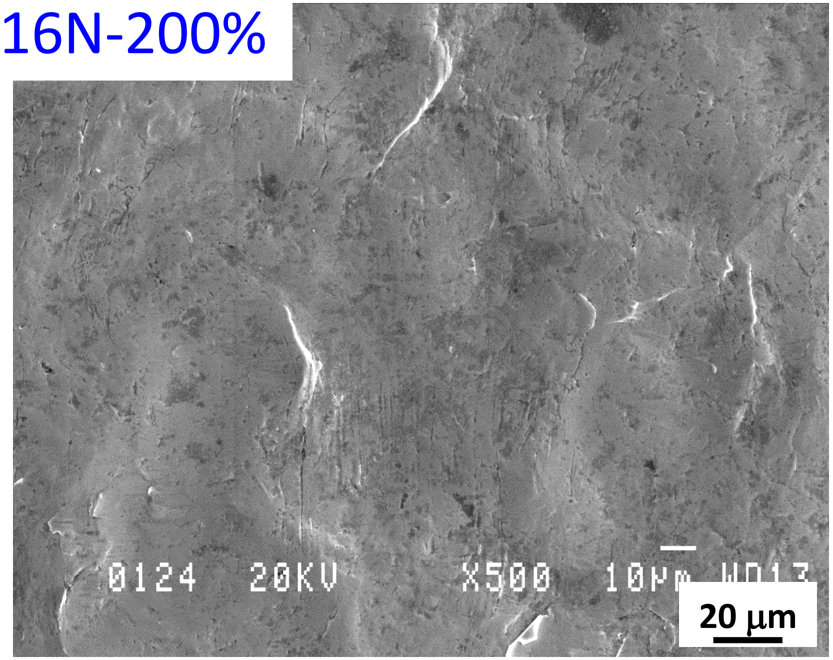
Shot peened 8N-200%





Shot peened 16N-200%





<u>Coated bars</u>

(4 pre-coat surface conditions)

- Highly polished (4 bars)
- Wet-blast (4 bars)
- Shot peened at 8N-200% (4 bars)
- Shot peened at 16N-200% (4 bars)

Coated with Ni-45Cr-0.1Y

<u>Uncoated bars</u>

- LSG+LP (6 bars)

Shot peening 16N-200%

Diffusion anneal, 8h/760°C, Low PO_2 (10^{-17} atm O_2)

<u>Oxidation exposure</u>

(500h/760°C, air)

<u>Hot corrosion exposure</u>

(50h/760°C, Na-Mg sulfate salts, air)

<u>LCF Testing (760°C)</u>

841/-427 Mpa, 0.33 hertz

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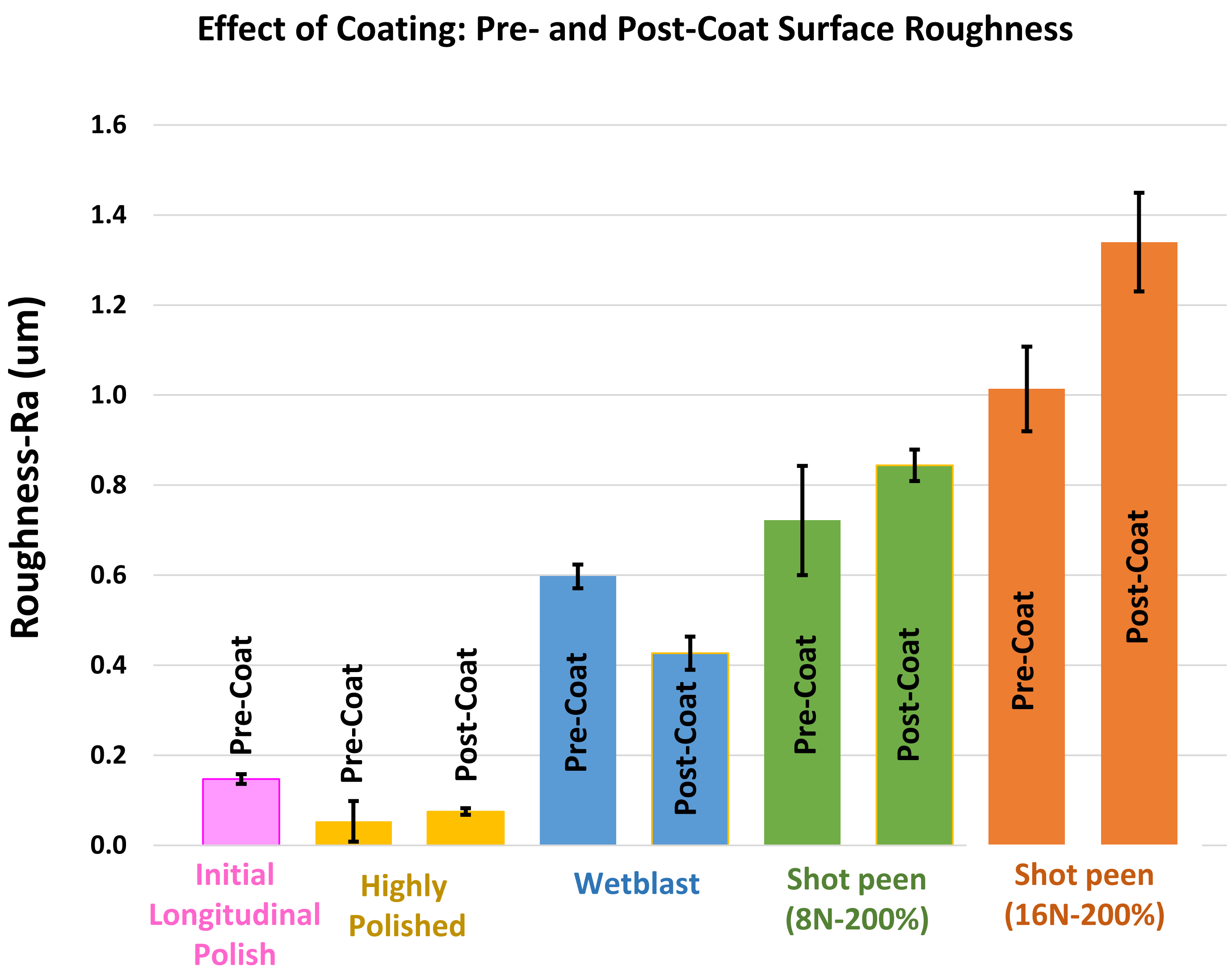
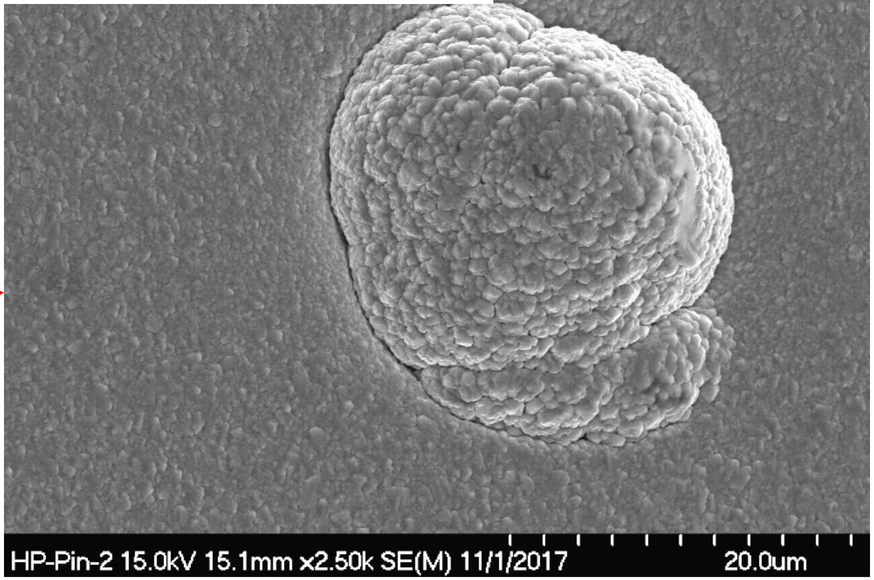
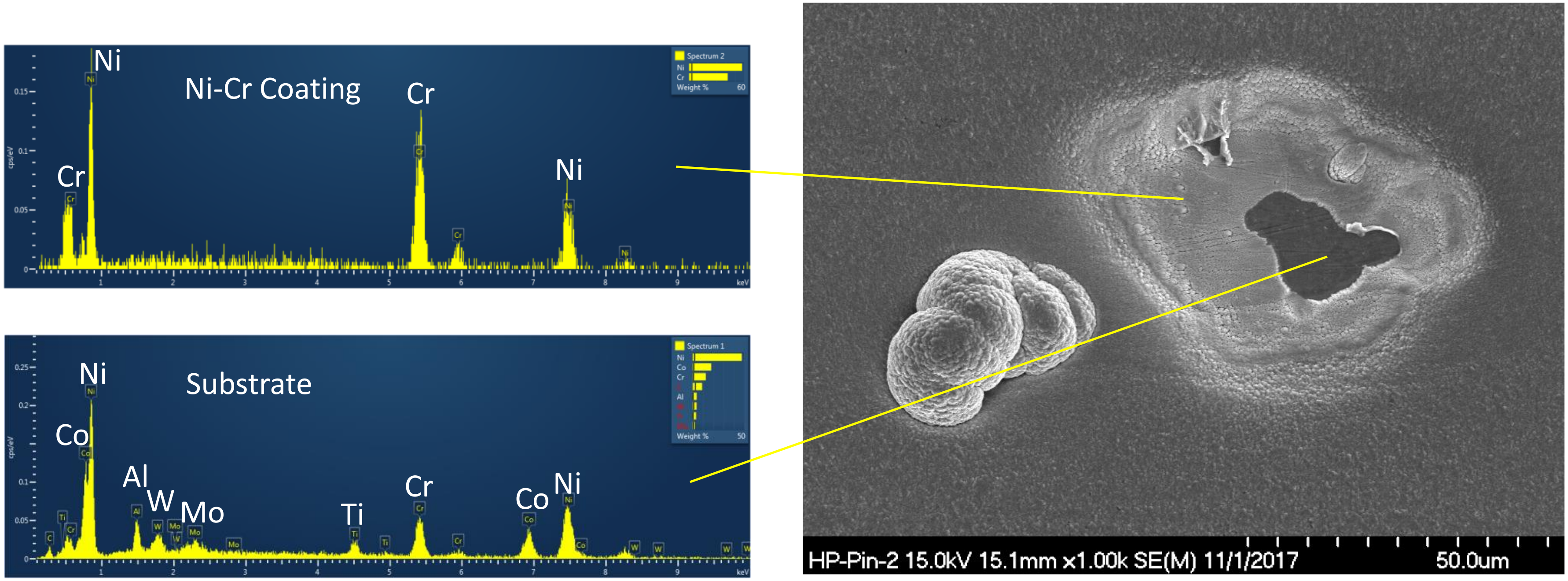
Surface Roughness after Coating

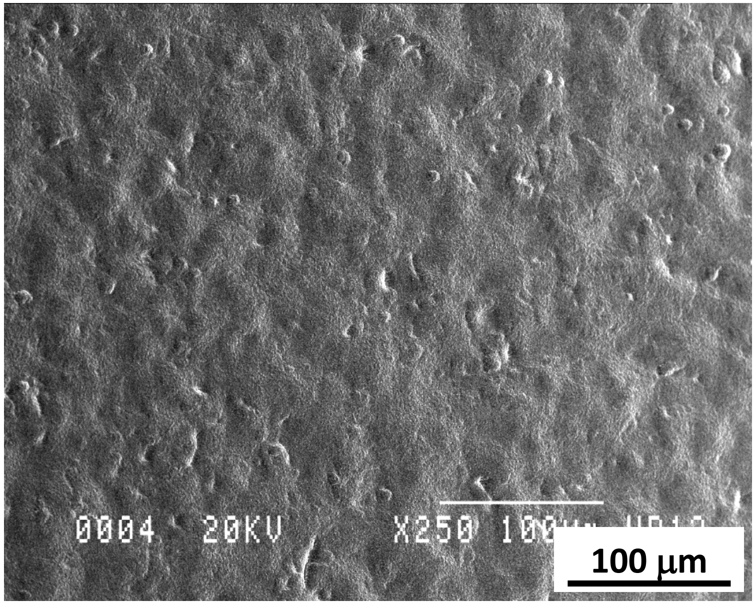


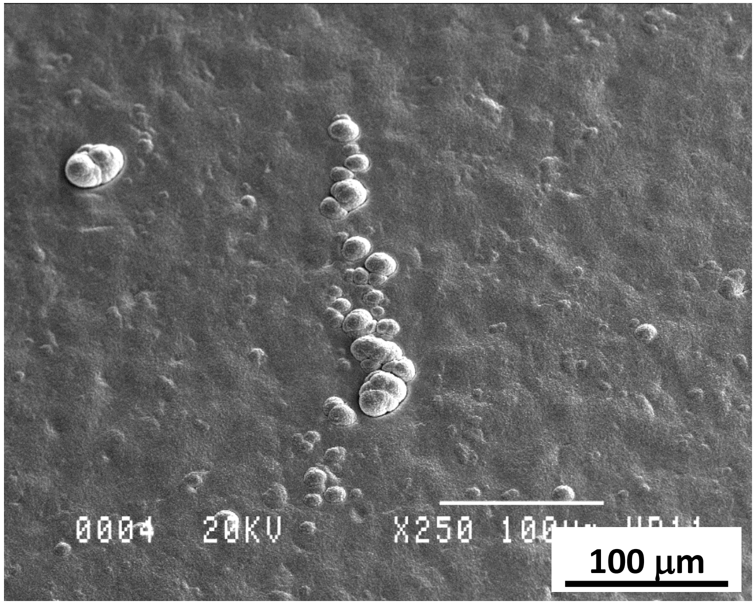
Highly-polished surface after coating

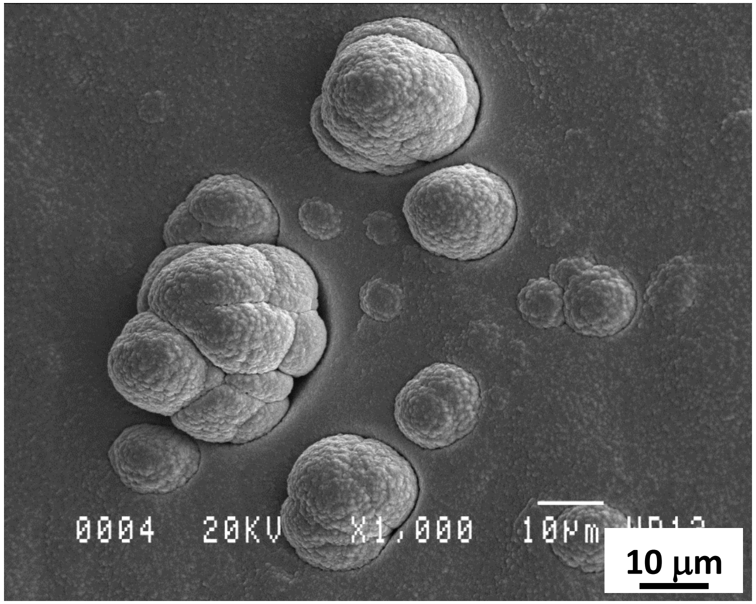




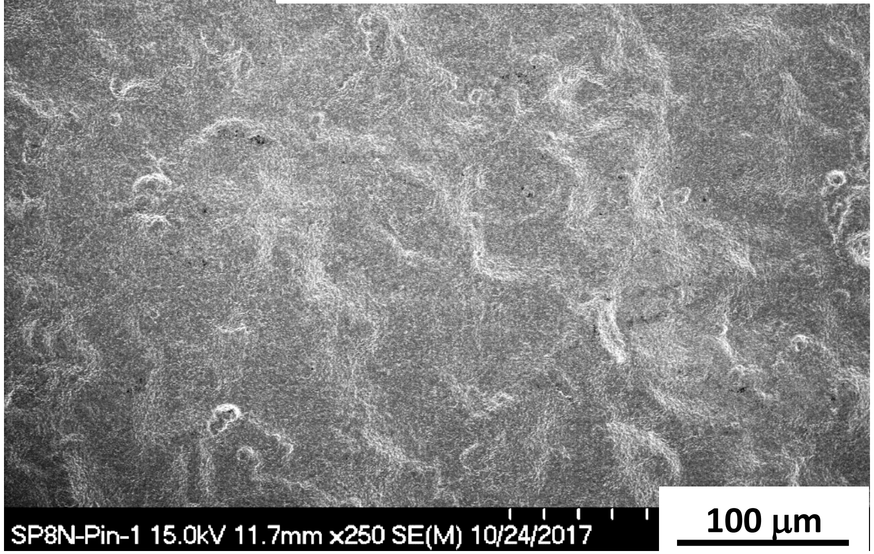
Wetblast surface after coating



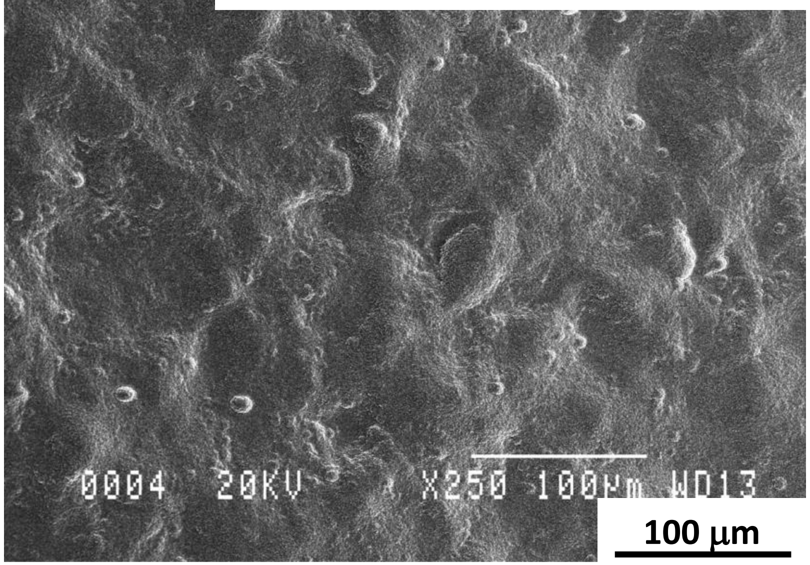


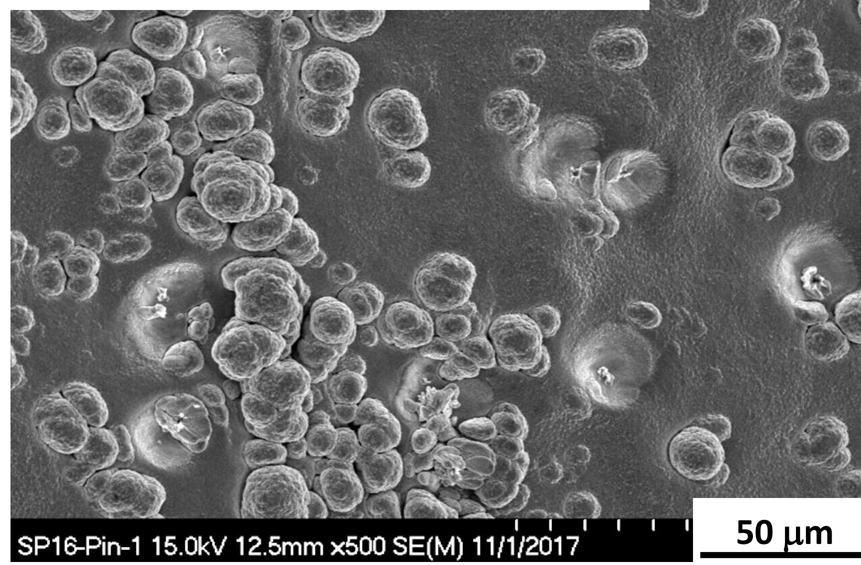


Shot-peened surface (8N-200%) after coating



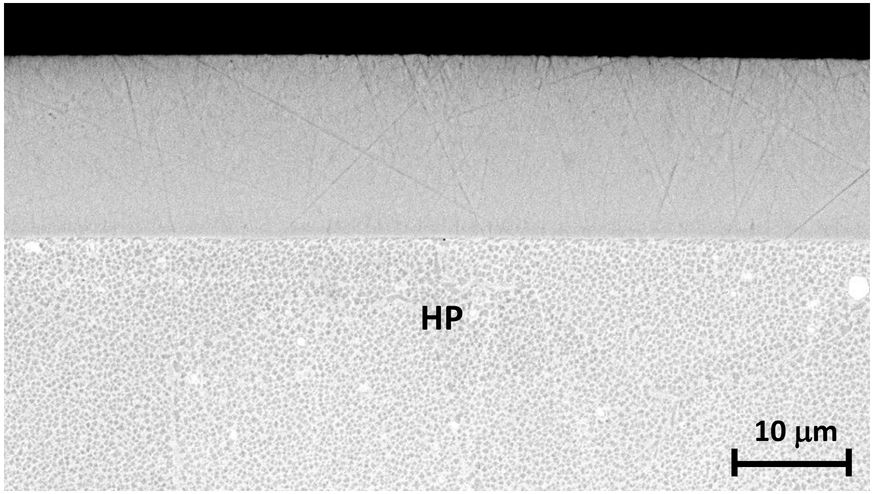
Shot-peened surface (16N-200%) after coating

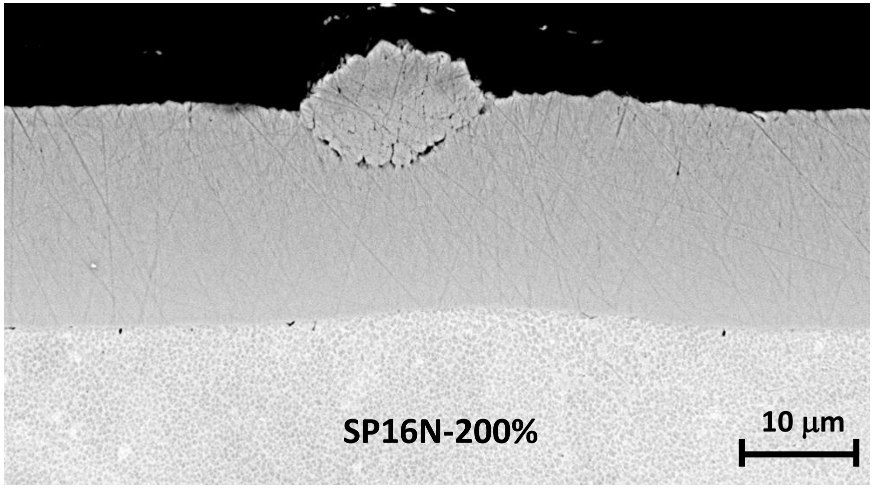


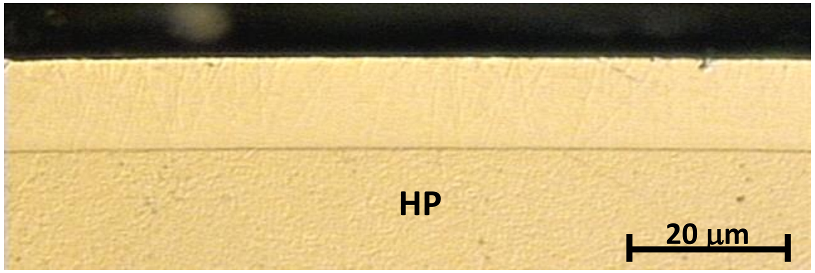


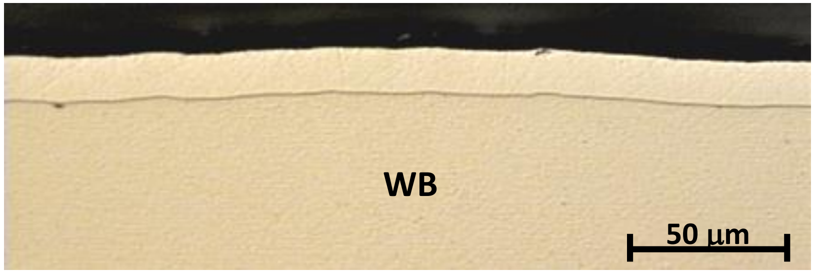
Ni45Cr-0.1Y Coating "as Coated"

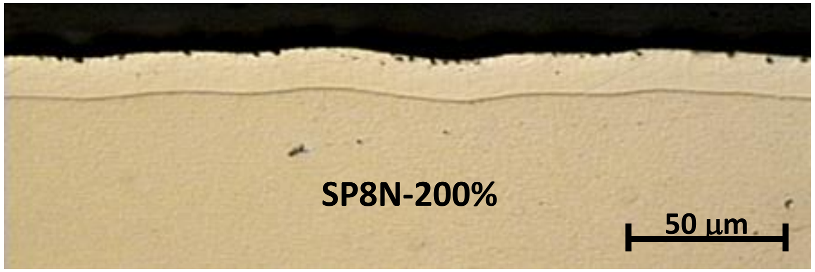
Coating thickness: 11-14 um (11.4-14.3 um)

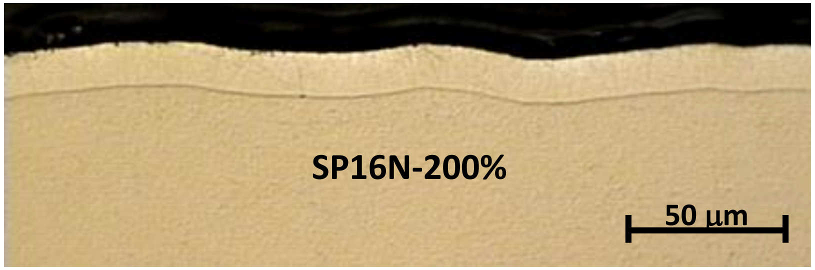












Coated bars

(4 pre-coat surface conditions)

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Coated with Ni-45Cr-0.1Y

Uncoated bars

- LSG+LP (6 bars)

Shot peening 16N-200%

Diffusion anneal, 8h/760°C, Low PO_2 (10^{-17} atm O_2)

Oxidation exposure

(500h/760°C, air)

Hot corrosion exposure

(50h/760°C, Na-Mg sulfate salts, air)

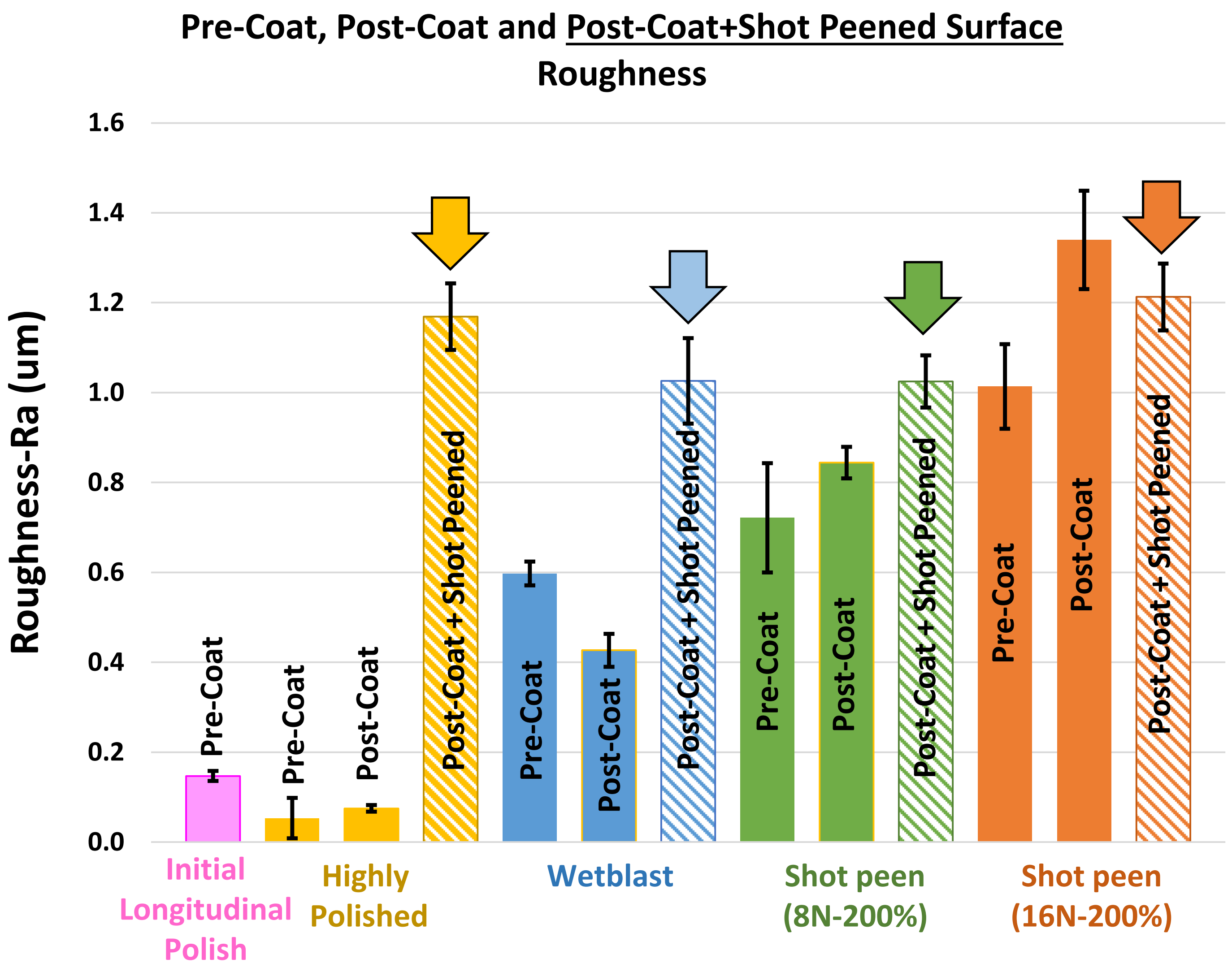
LCF Testing (760°C)

841/-427 Mpa, 0.33 hertz

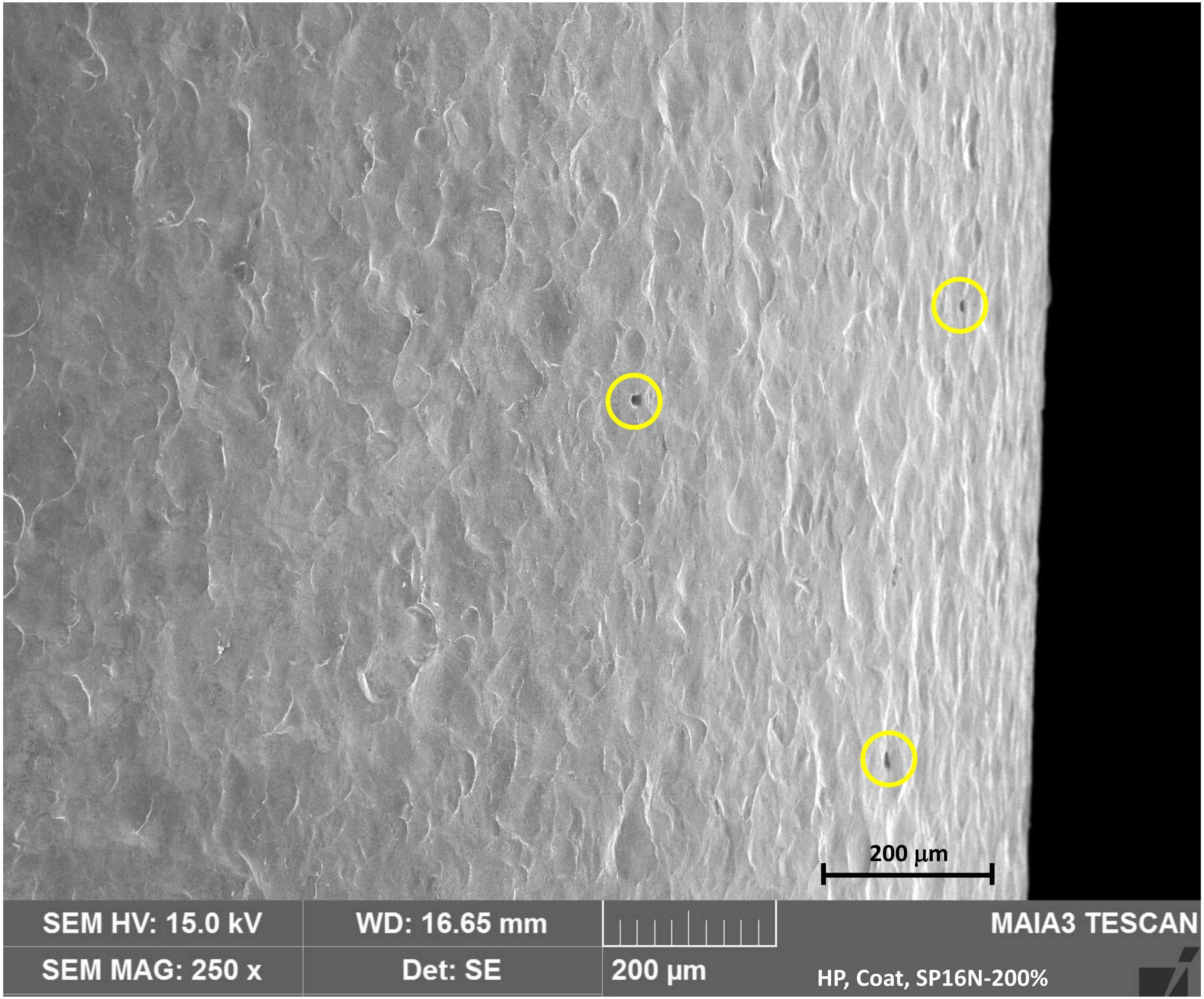
LCF Testing (760°C)

841/-427 Mpa, 0.33 hertz

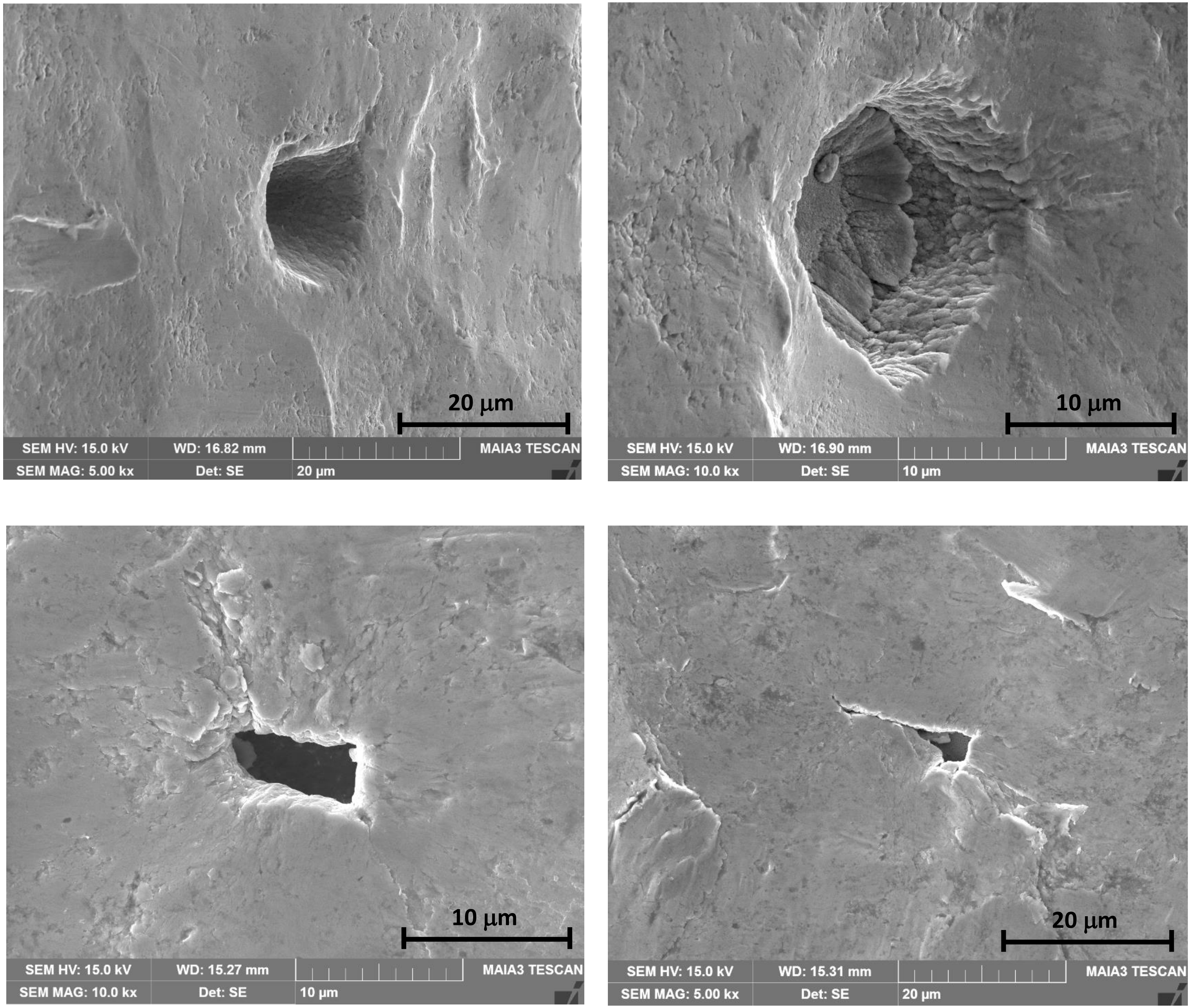
Surface Roughness after Coating + Shot Peening (16N-200%)



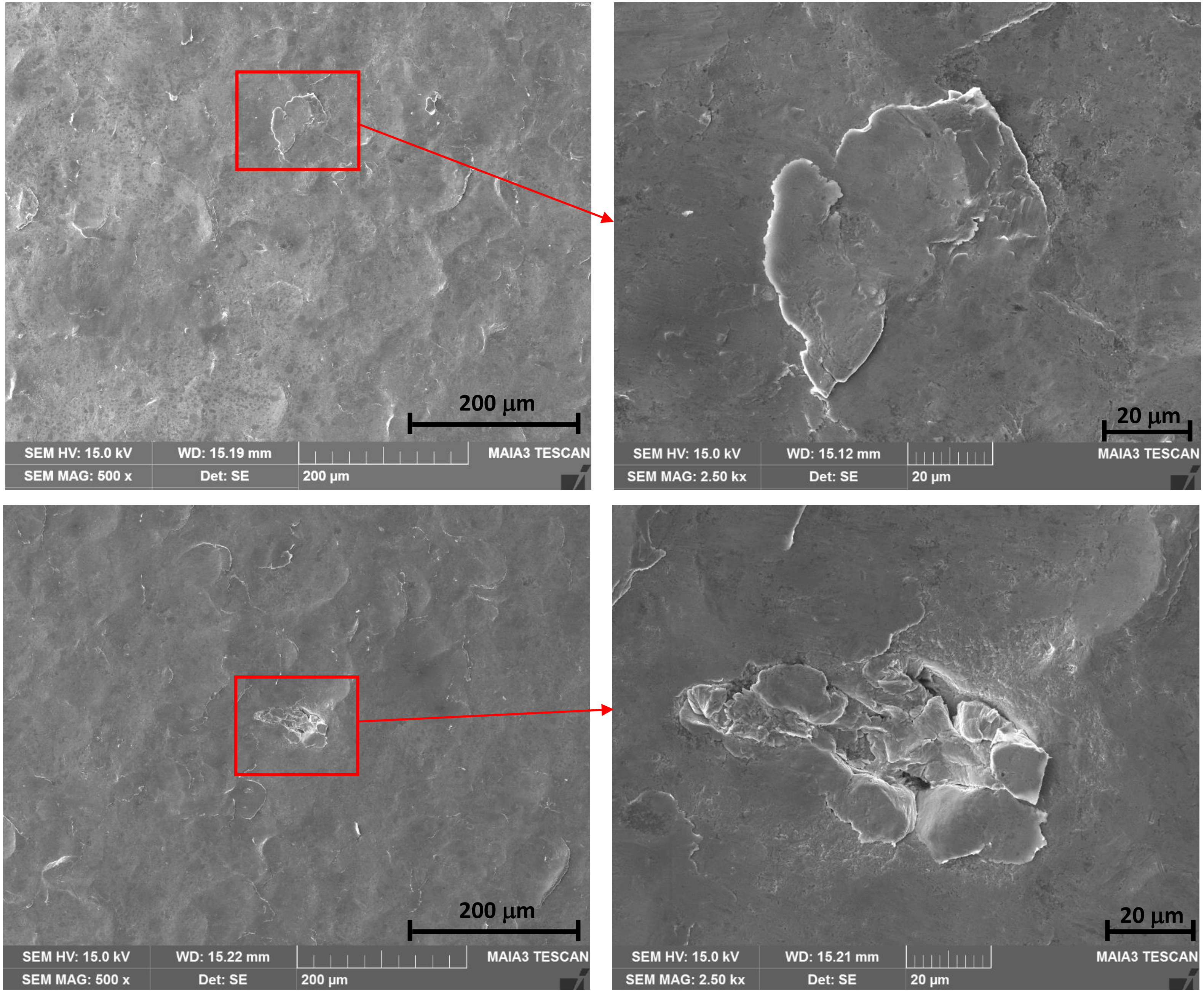
Coated Surface (HP) “as-Shot Peened”



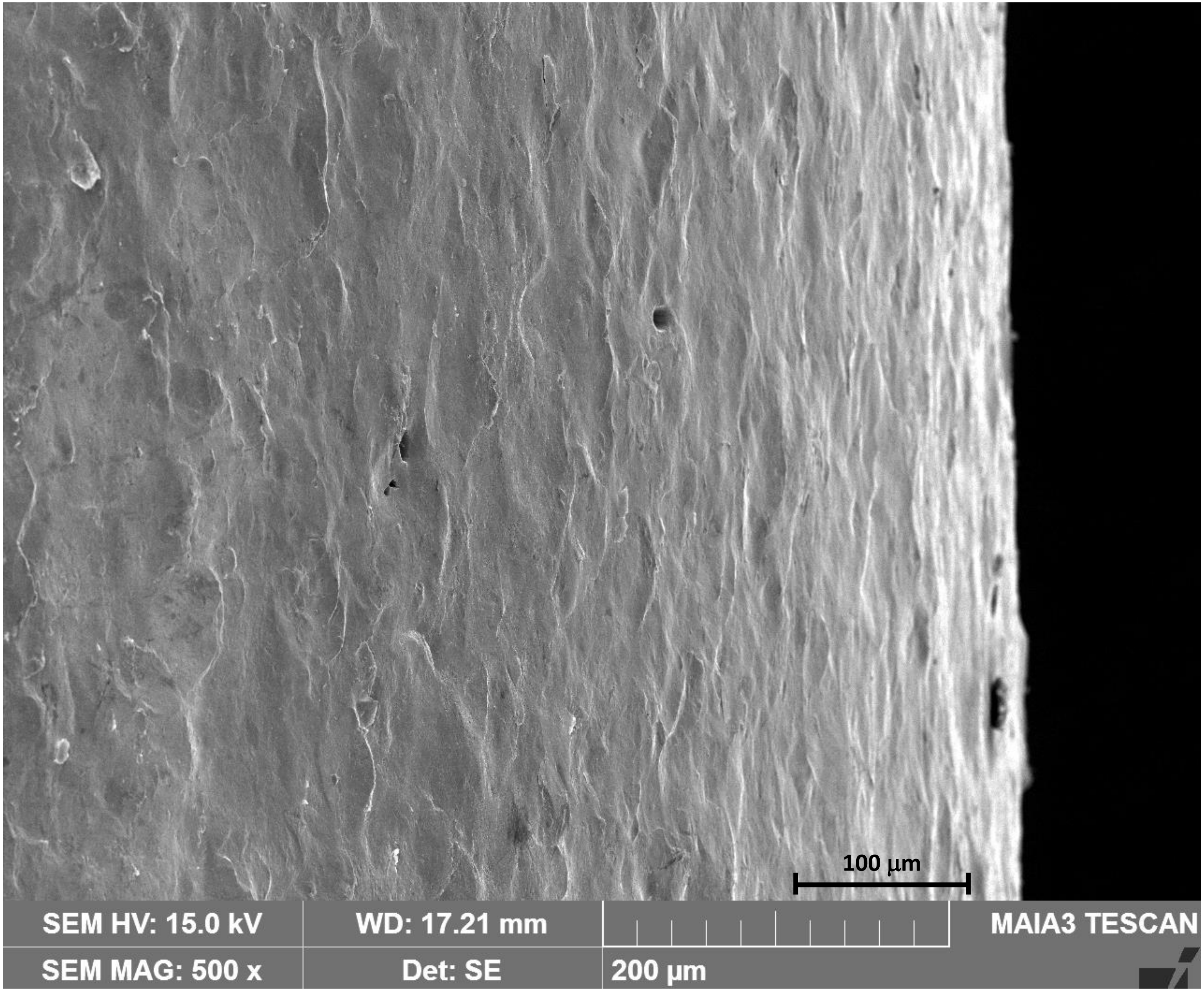
Coated Surface (HP) “as-Shot Peened”



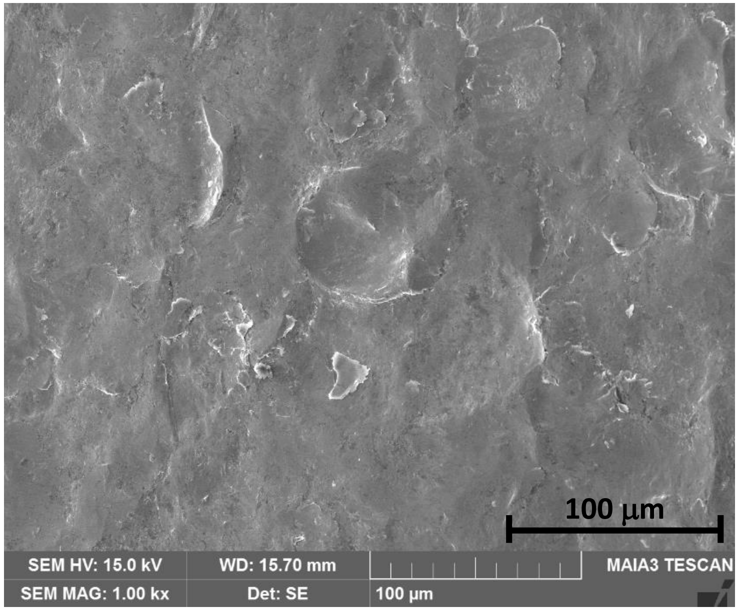
Coated Surface “as-Shot Peened”

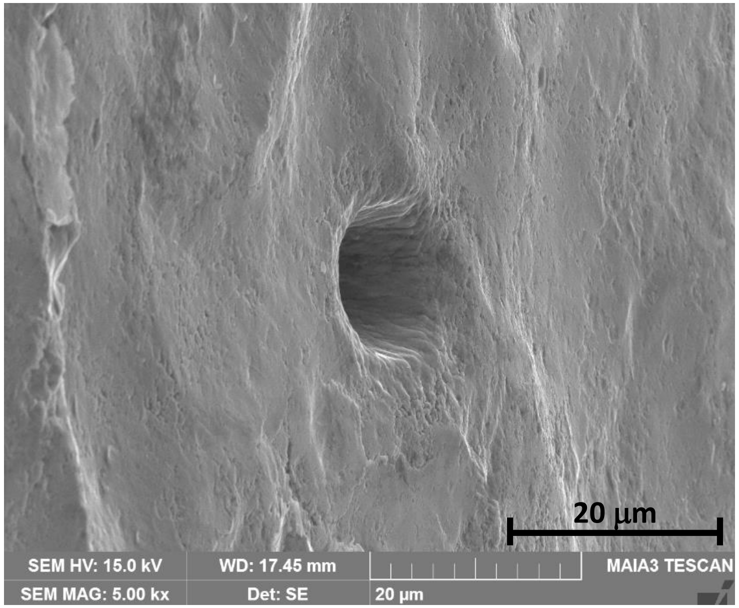


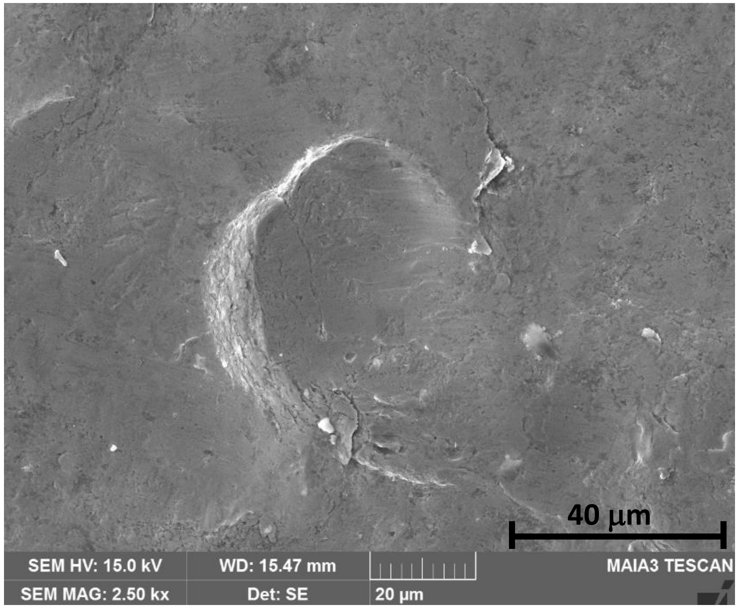
Coated Surface (SP16N) "as-Shot Peened"

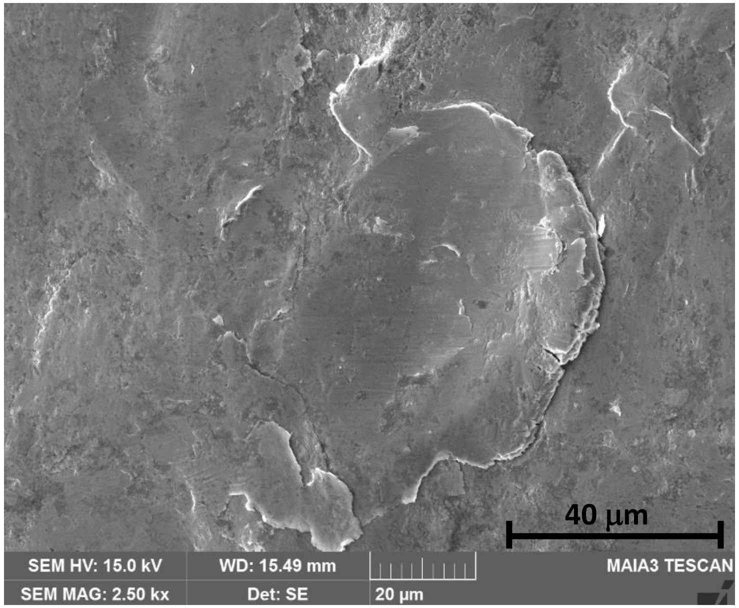


Coated Surface (SP16N) “as-Shot Peened”

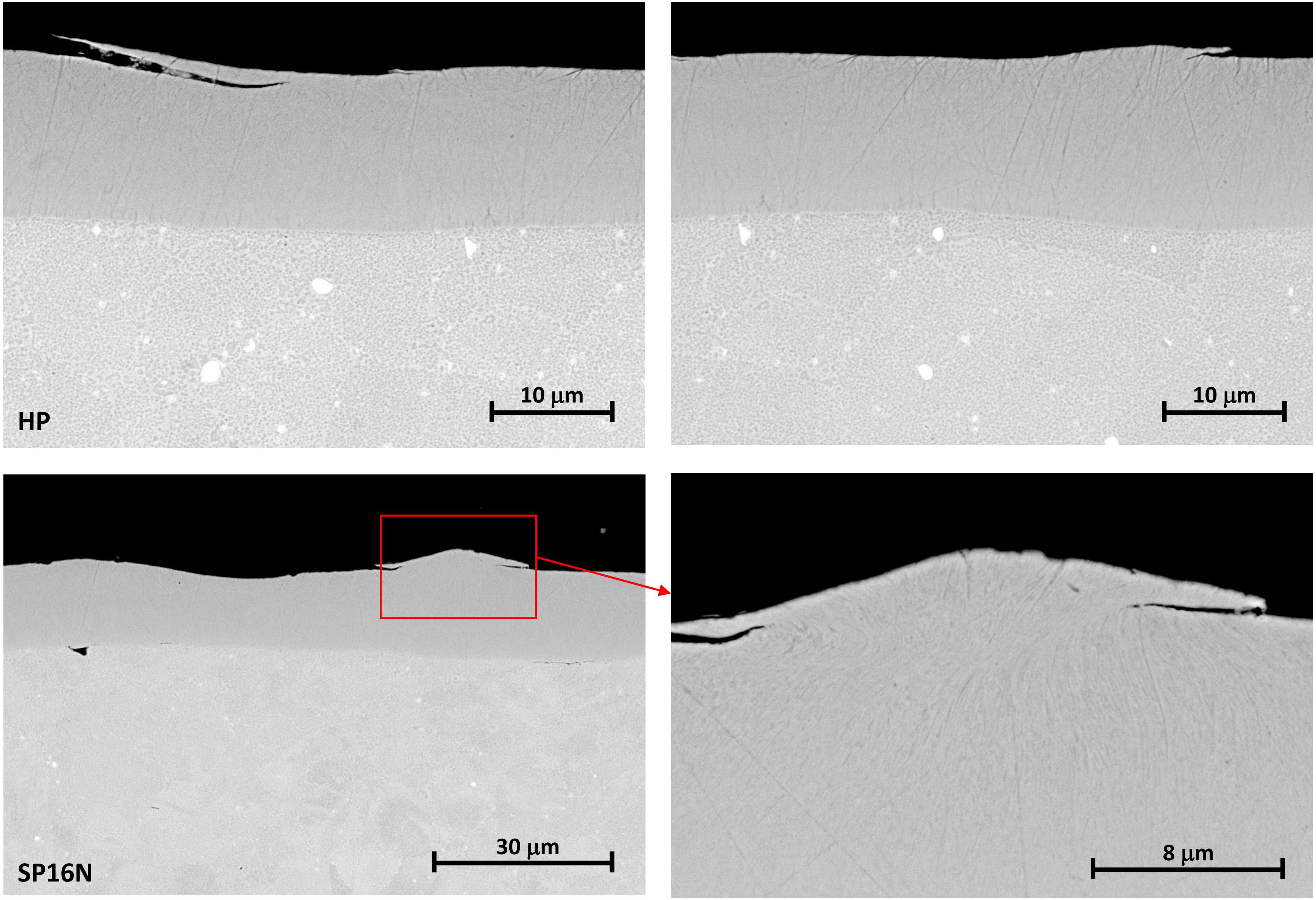








Post-Shot Peen



Coated bars

(4 pre-coat surface conditions)

- Highly polished (4 bars)
- Wet-blast (4 bars)
- Shot peened at 8N-200% (4 bars)
- Shot peened at 16N-200% (4 bars)

Coated with Ni-45Cr-0.1Y

Uncoated bars

- LSG+LP (6 bars)

Shot peening 16N-200%

Diffusion anneal, 8h/760°C, Low PO_2 (10^{-17} atm O_2)

Oxidation exposure

(500h/760°C, air)

Hot corrosion exposure

(50h/760°C, Na-Mg sulfate salts, air)

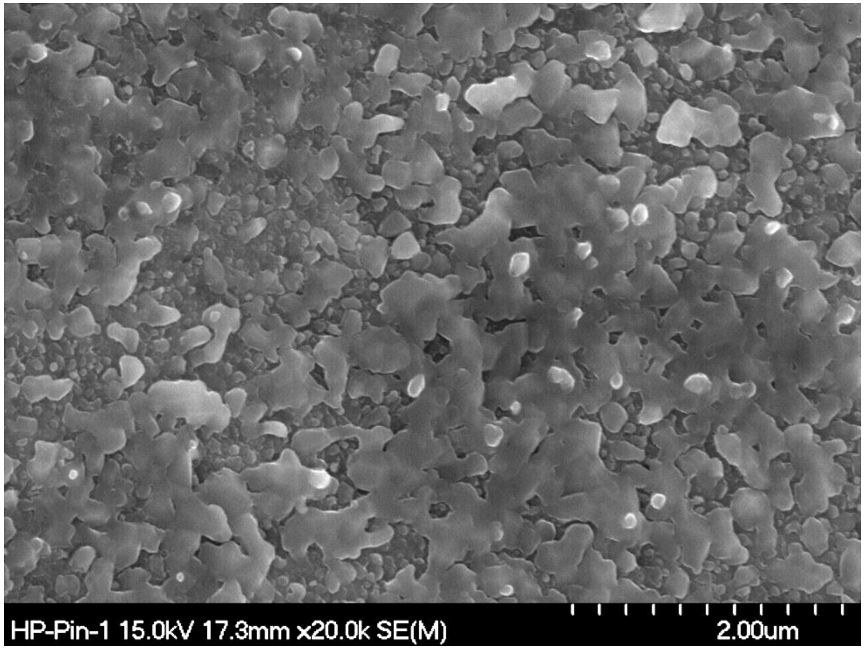
LCF Testing (760°C)

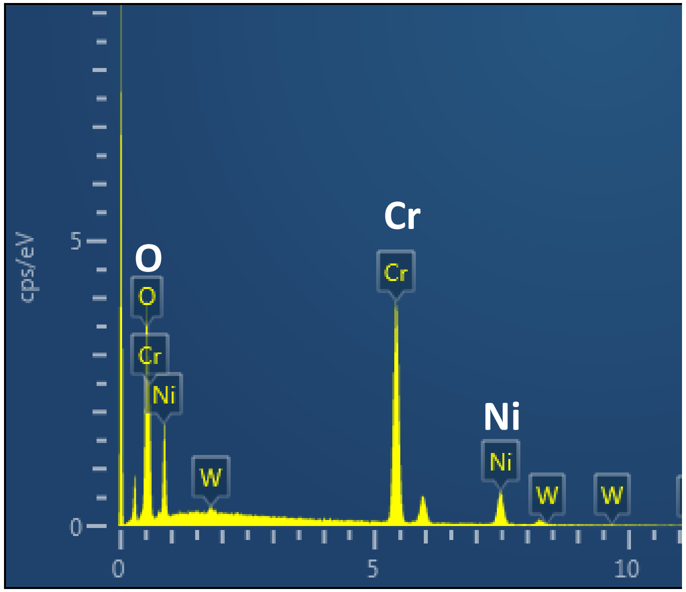
841/-427 Mpa, 0.33 hertz

LCF Testing (760°C)

841/-427 Mpa, 0.33 hertz

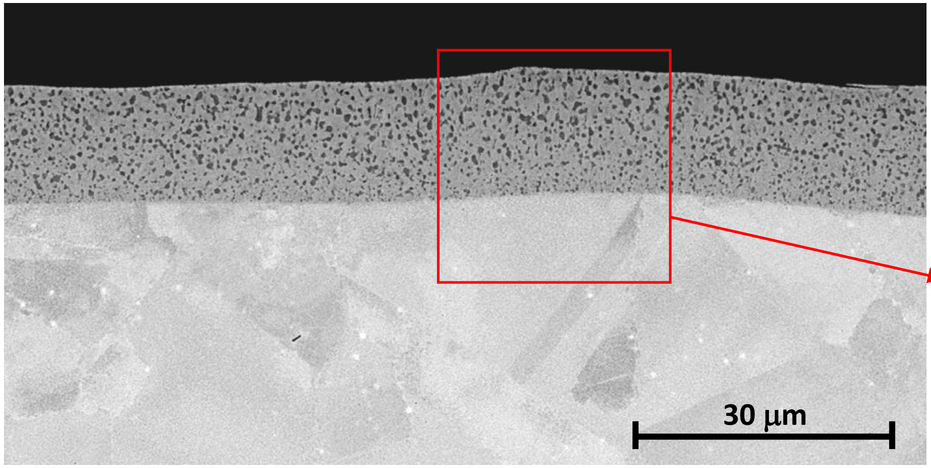
Diffusion anneal, 8h/760°C, Low PO_2 (10^{-17} atm O_2)

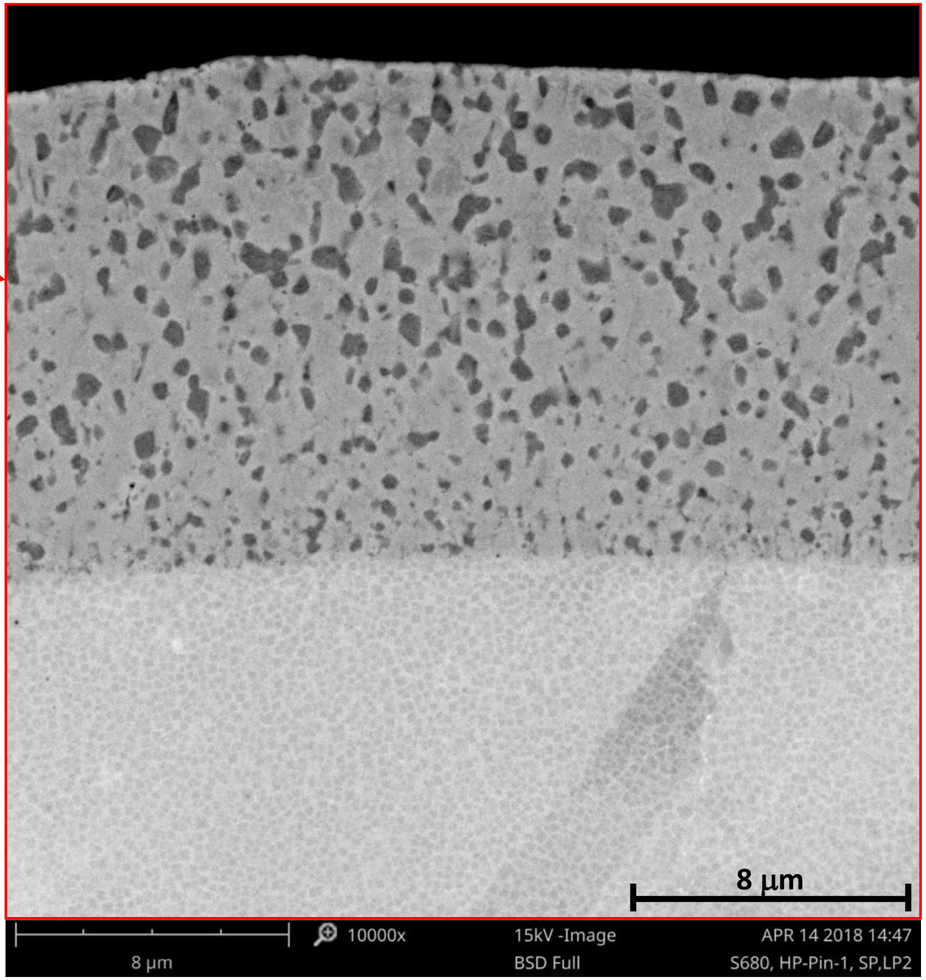


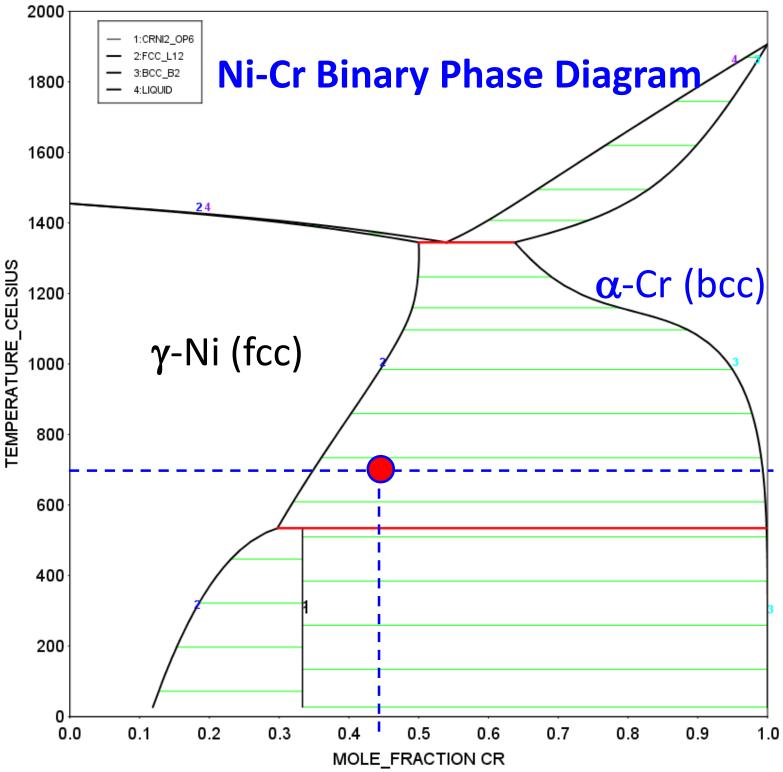


Very thin scale of Cr_2O_3

Diffusion anneal, 8h/760°C, Low PO_2 (10^{-17} atm O_2)







Dark, 2nd phase is α-Cr (high 90's %Cr)

Coated bars

(4 pre-coat surface conditions)

- Highly polished (4 bars)
- Wet-blast (4 bars)
- Shot peened at 8N-200% (4 bars)
- Shot peened at 16N-200% (4 bars)

Coated with Ni-45Cr-0.1Y

Uncoated bars

- LSG+LP (6 bars)

Shot peening 16N-200%

Diffusion anneal, 8h/760°C, Low PO_2 (10^{-17} atm O_2)

Oxidation exposure

(500h/760°C, air)

Hot corrosion exposure

(50h/760°C, Na-Mg sulfate salts, air)

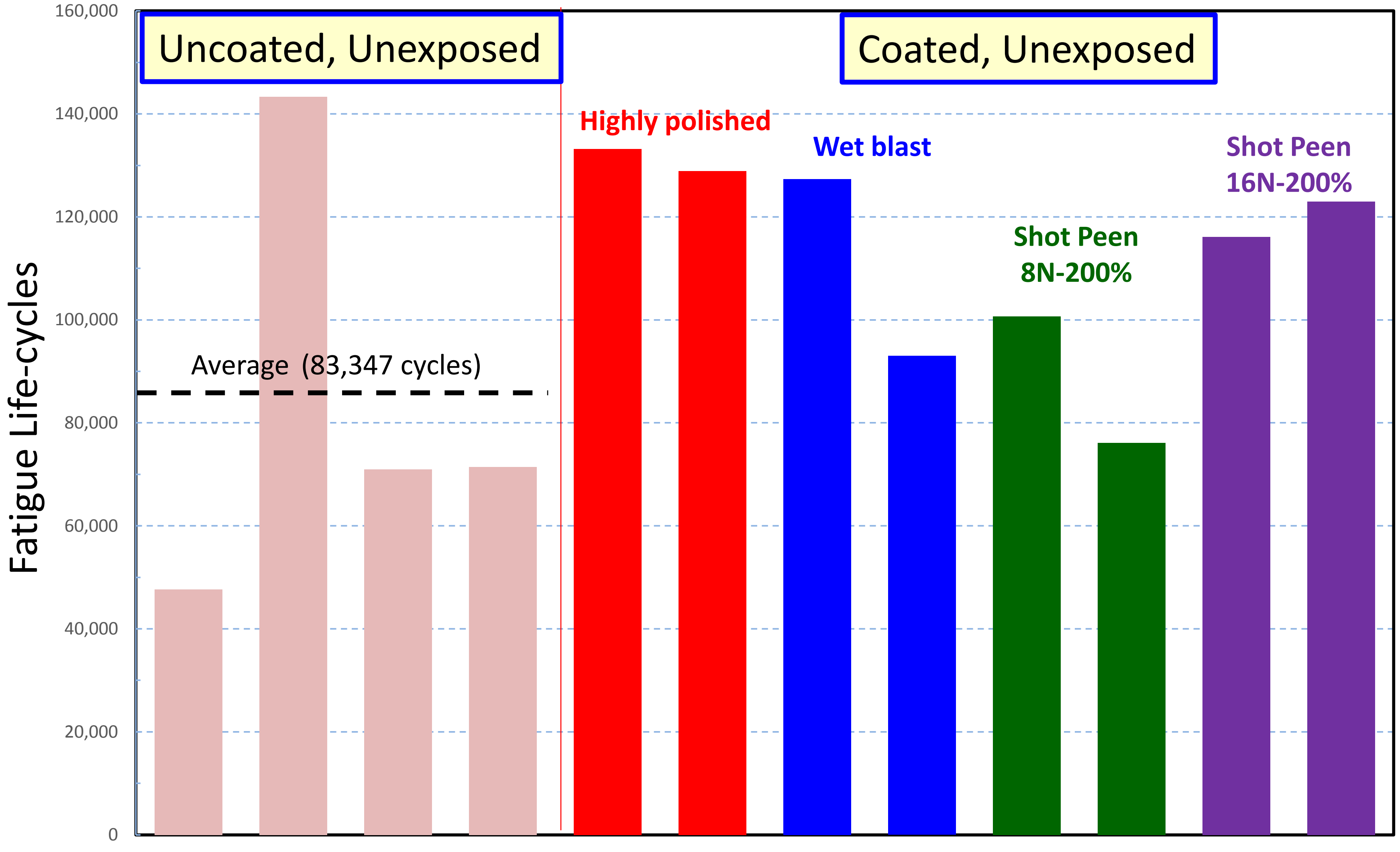
LCF Testing (760°C)

841/-427 Mpa, 0.33 hertz

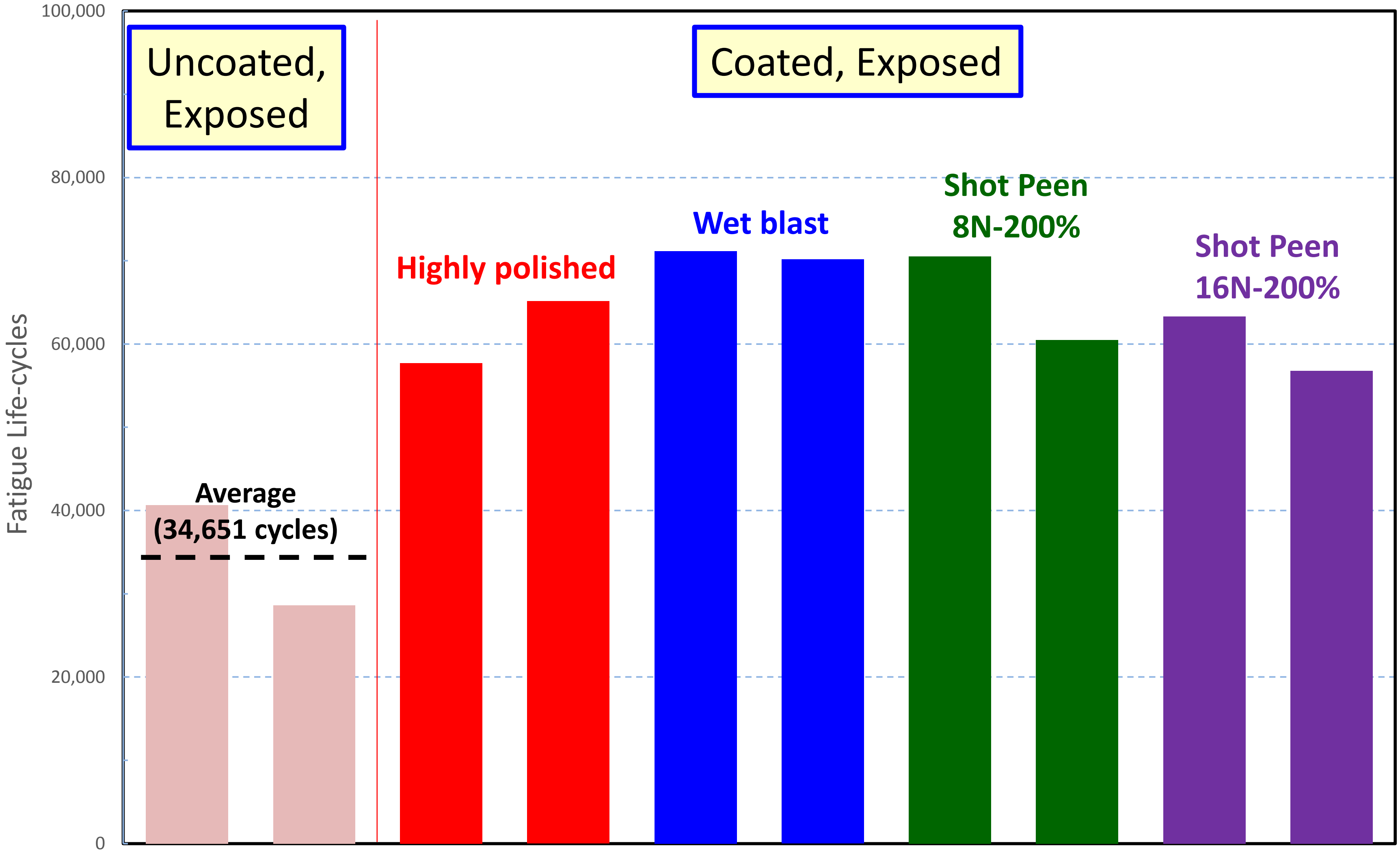
LCF Testing (760°C)

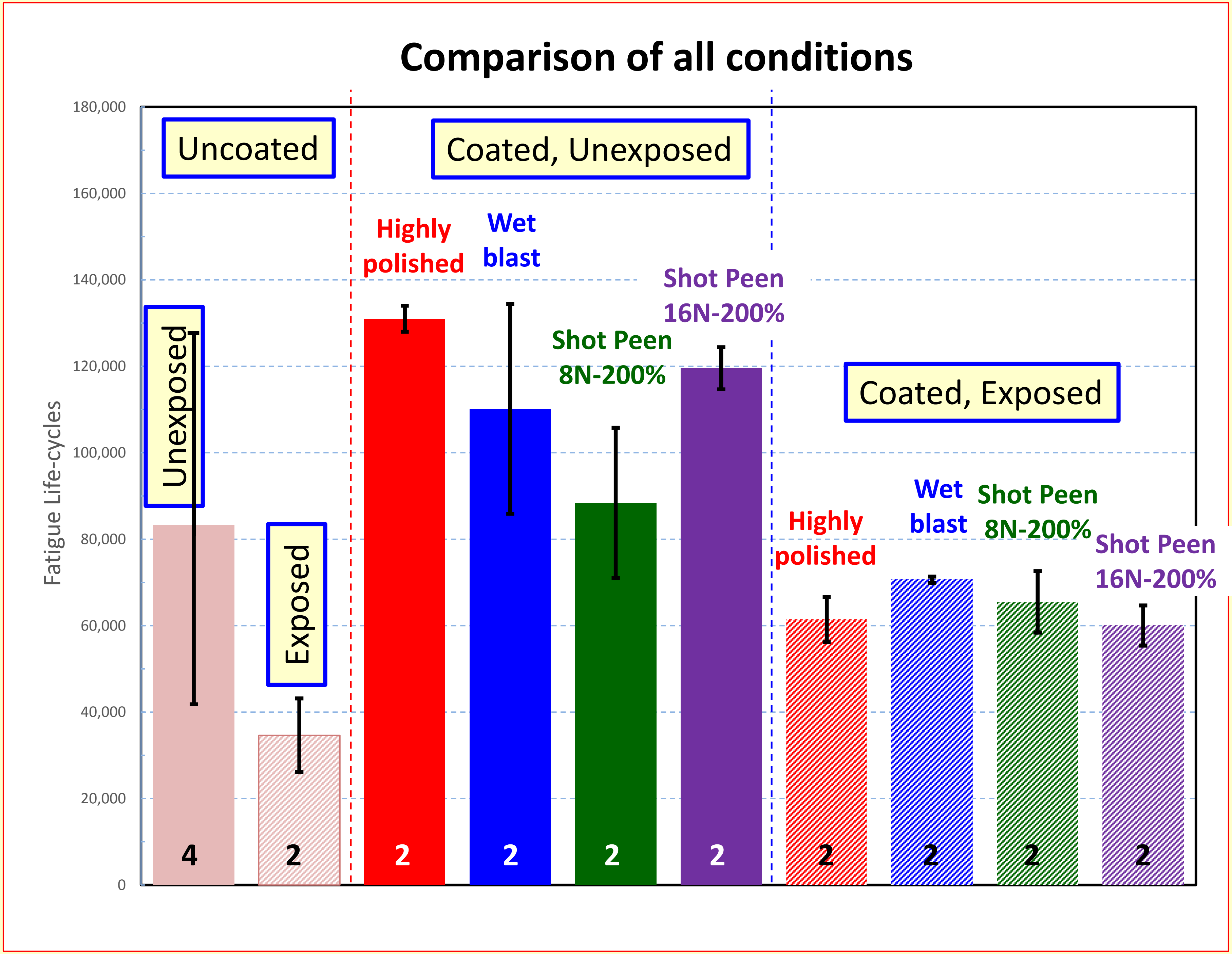
841/-427 Mpa, 0.33 hertz

Comparison of Unexposed Bars, Uncoated and Coated



Comparison of Exposed Bars, Uncoated and Coated

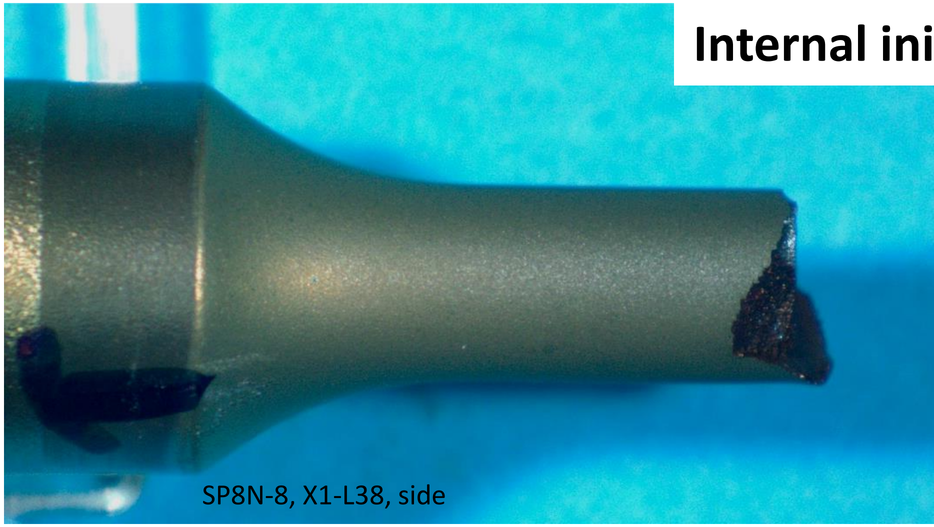


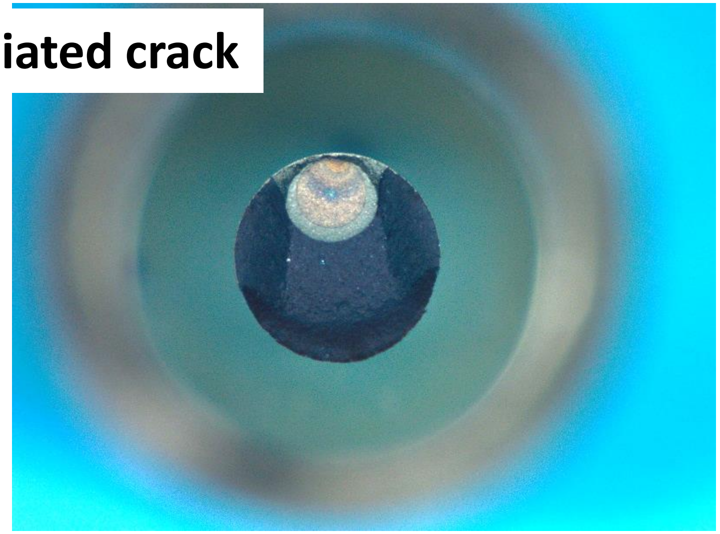


Comparison of all conditions
Fatigue Life-cycles
0
20,000
40,000
60,000
80,000
100,000
120,000
140,000
160,000
180,000
Uncoated
Unexposed
Exposed
Coated, Unexposed
Highly polished
Wet blast
Shot Peen 8N-200%
Shot Peen 16N-200%
Coated, Exposed
Highly polished
Wet blast
Shot Peen 8N-200%
Shot Peen 16N-200%
4
2
2
2
2
2
2
2
2
2

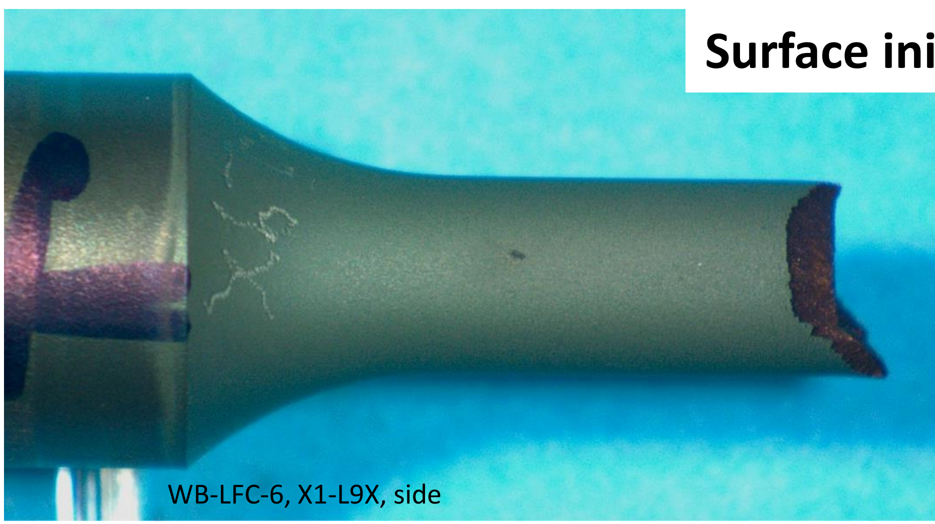
Where did the failure crack initiate?

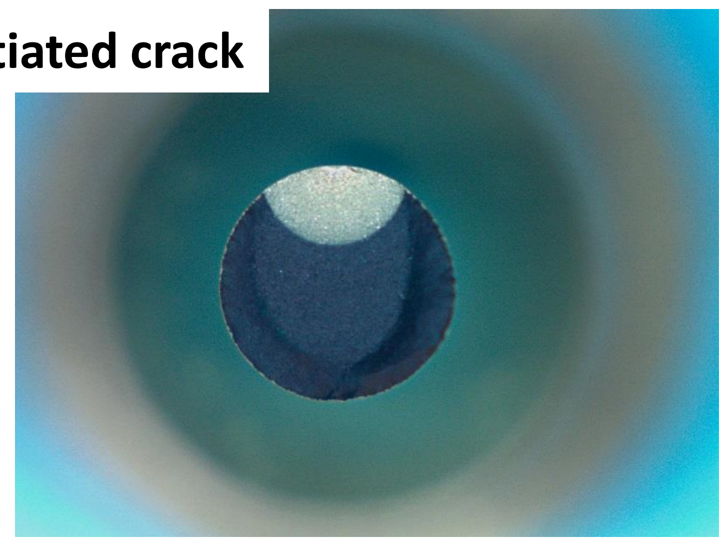
Internal initiated crack



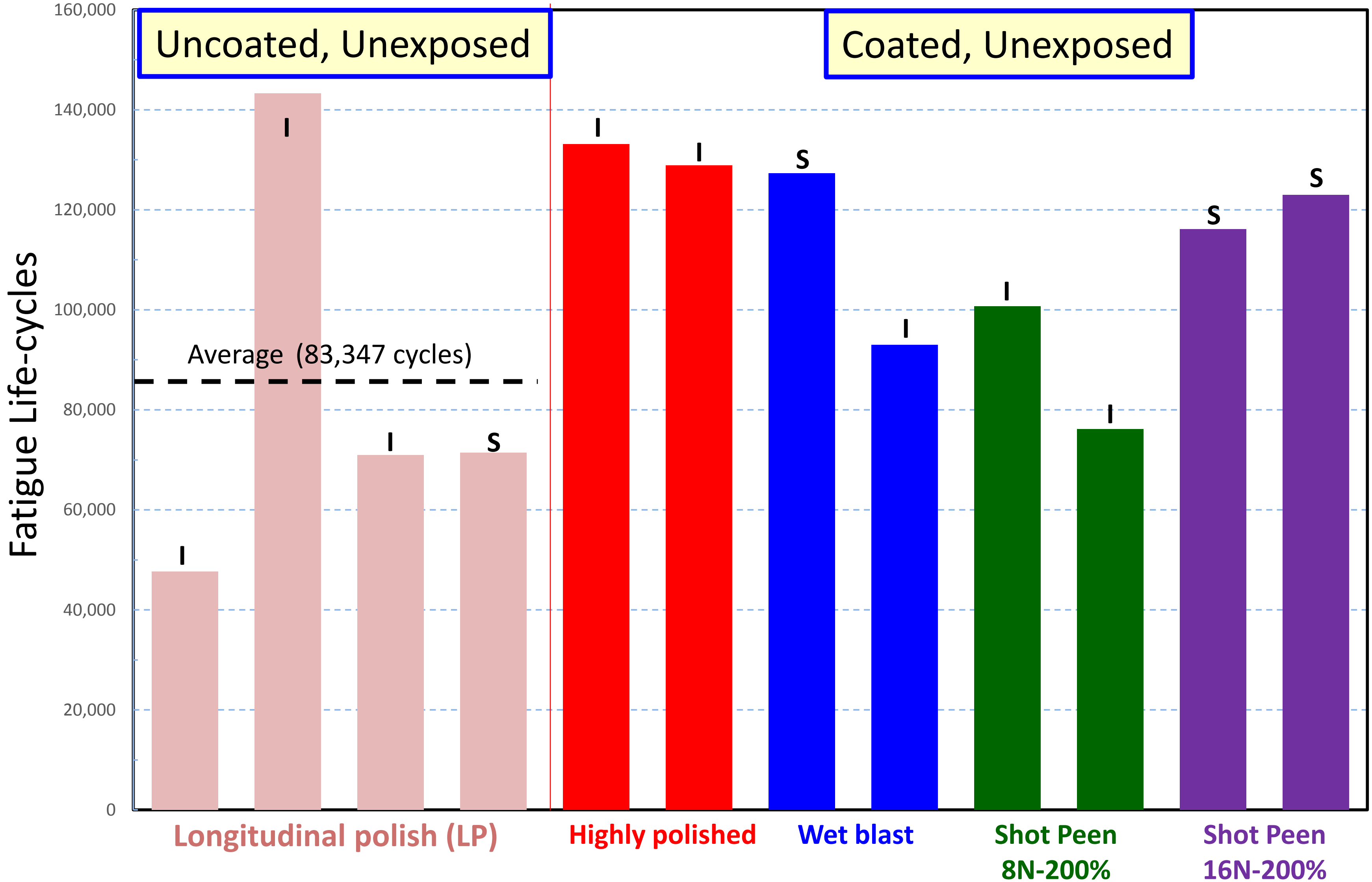


Surface initiated crack

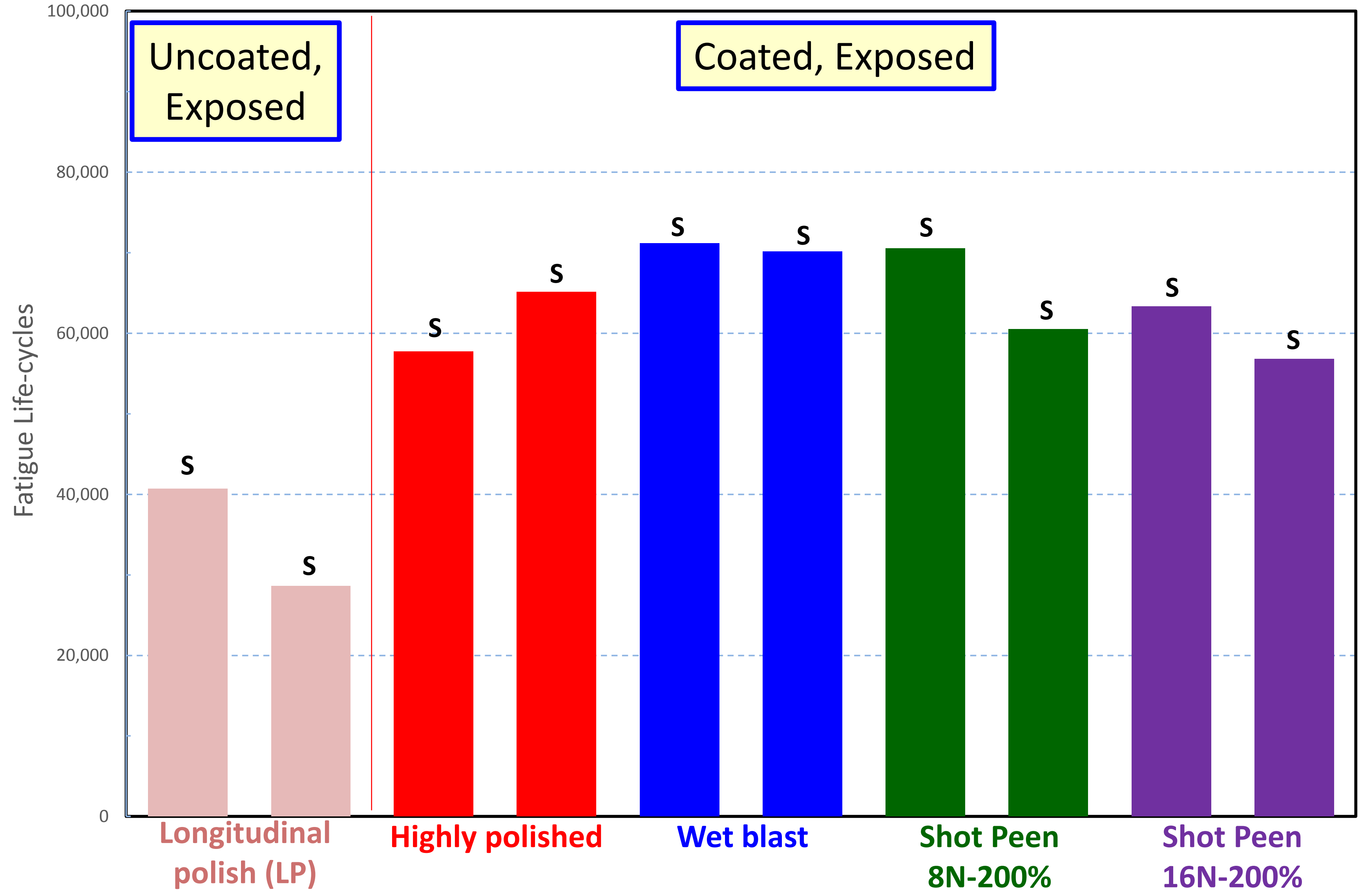




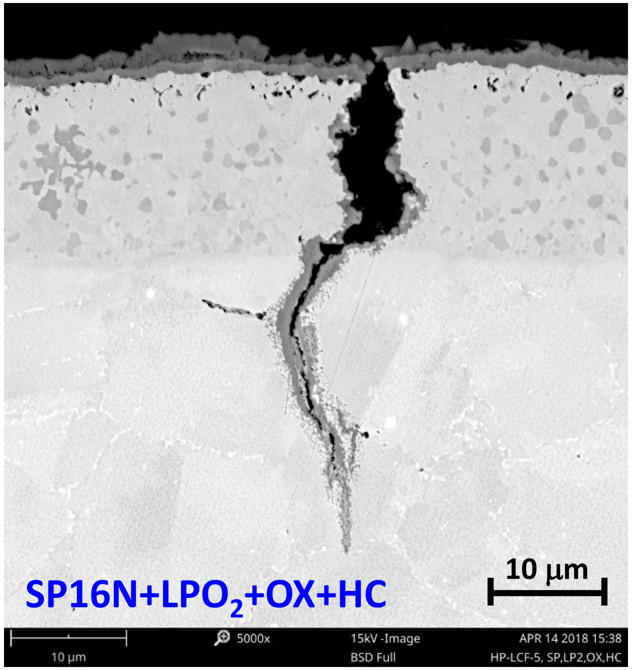
Comparison of Unexposed Bars, Uncoated and Coated

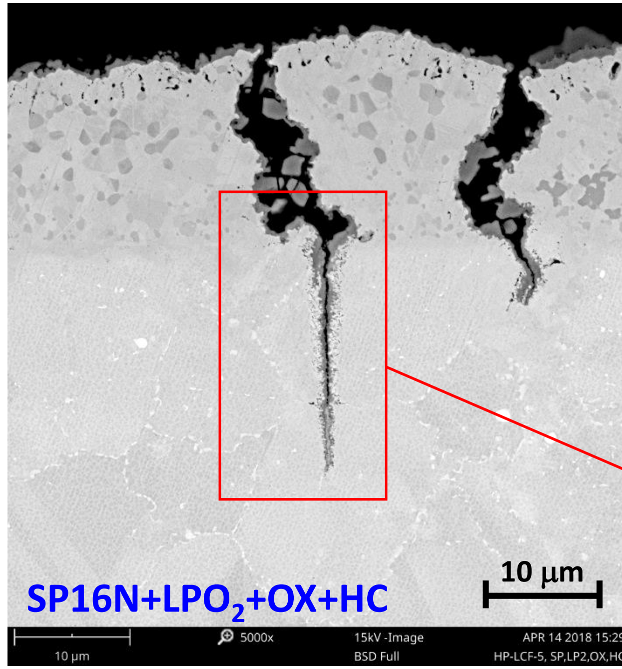


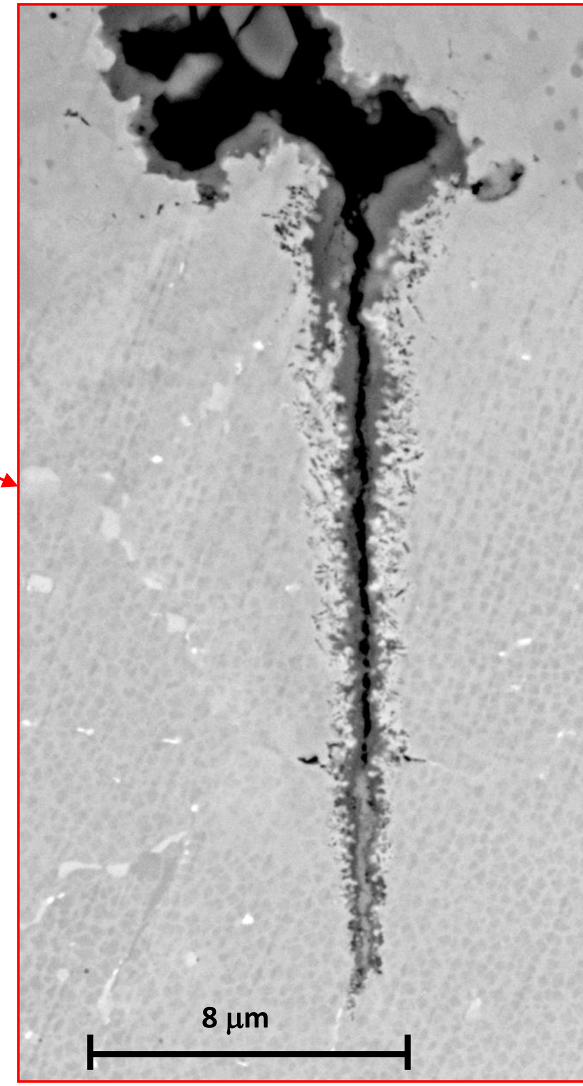
Comparison of Exposed Bars, Uncoated and Coated

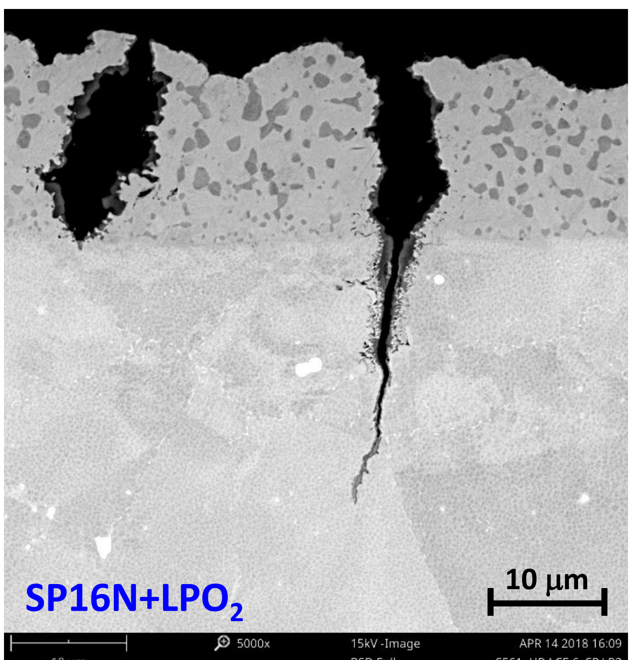


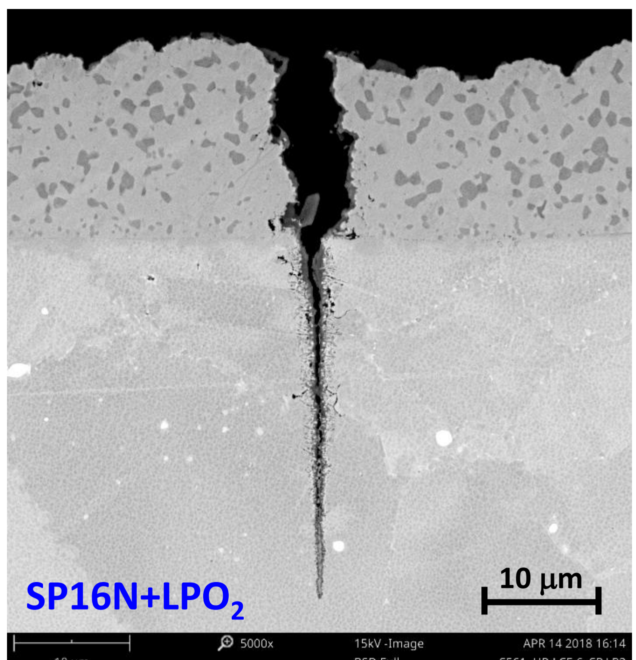
Post LCF Testing



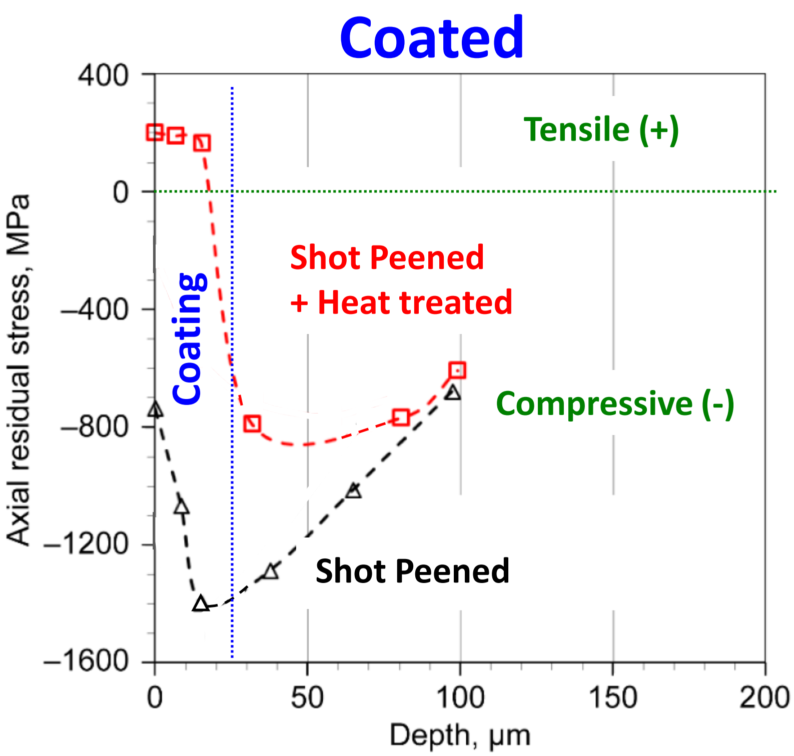


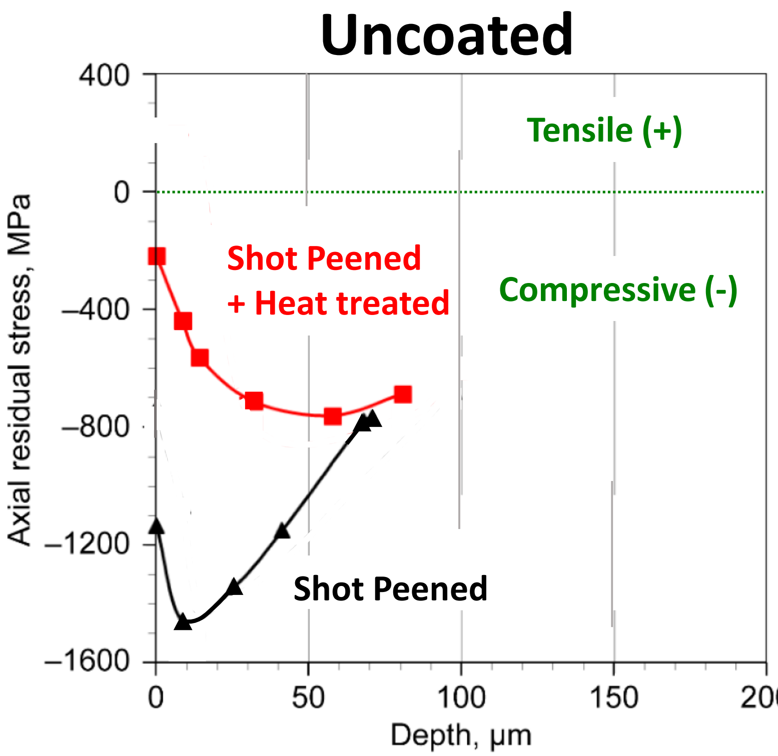






Stress at and below the surface*





* T. Gabb et al., “Influences of Processing and Fatigue Cycling on Residual Stresses in a NiCrY-Coated Powder Metallurgy Disk Superalloy,” Journal of Materials Engineering and Performance, 2017

<u>Conclusions:</u>

- Without exposures, the coating did not degrade the LCF life of the bars.
- After oxidation and hot corrosion, the LCF lives of the coated bars was 1.7-2X higher than that for the uncoated bars.
- After oxidation and hot corrosion, the primary crack leading to failure always initiated at the surface whether coated or uncoated.
- There was not an obvious "winner" between the four pre-coat treatments; wet-blast or shot peen could likely both be adopted for use with disks

Future Directions:

- Explore effect of high and low Cr coating compositions.
- Explore stronger, more crack-resistant coatings with sufficient Cr to maintain corrosion resistance.

Acknowledgements

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